

Present status and future directions – Minimal endodontic access cavities

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Abstract

In the last decades, the move of medicine towards minimally invasive treatments is notorious and scientifically grounded. As dentistry naturally follows in its footsteps, minimal access preparation have also become a trend topic in the endodontic field. This procedure aims to maximize preservation of dentine tissue backed up by the idea that this is an effective way to reduce the incidence of post-treatment tooth fracture. However, with the assessment of the body of evidence on this topic, it is possible to observe some key points (a) the demand for nomenclature standardization, (b) the requirement of specific tools such as ultra-flexible instruments, visual magnification, superior illumination, and three-dimensional imaging technology, (c) minimally invasive treatment does not seem to affect orifice location and mechanical preparation when using adequate armamentarium, but it (d) may impair adequate canal cleaning, disinfection and filling procedures, and also (e) it displays contradictory results regarding the ability to increase the tooth strength compared to the traditional access cavity. In spite of that, it is undeniable that methodological flaws of some bench-top studies using extracted teeth may be responsible for the conflicting data, thus triggering the need for more sophisticated devices/facilities and specifically designed research in an attempt to make clear the role of the access size/design on long-term teeth survival. Moreover, it is inevitable that a clinical approach such as minimal endodontic access cavities that demands complex tools and skilled and experienced operators bring to the fore doubts on its educational impact mainly when confronted with the conflicting scientific output, ultimately provoking a cost-benefit analysis of its implementation as a routine technique. In addition, this review discusses the ongoing scientific and clinical status of minimally invasive access cavities aiming to input an in-depth and unbiased view over the rationale behind them, uncovering not only the related conceptual and scientific flaws but also outlining future directions for research and clinical practices. The conclusions attempt to skip from passionate disputes highlighting the current body of evidence as weak and incomplete to guide decision making, demanding the development of a close-to-*in situ* laboratory model or a large and well-controlled clinical trial to solve this matter.

KEYWORDS

conservative endodontic cavity, endodontics, fracture resistance, minimal access cavity preparation, minimally invasive access cavity, root canal treatment

INTRODUCTION

The minimally invasive concept emphasizes the imperative to preserve the structural integrity of the original tissues, minimizing harm to patients and maximizing the natural self-healing power of the central immune system to fight against disease (Murdoch-Kinch & McLean, 2003). In the last few decades, medicine has been moving towards this concept based on the substantial developments in the field of microsystem engineering, nanotechnology, laser application, and high-resolution imaging for diagnosis and guidance of surgical instruments. Dentistry naturally followed this trend, and in the specific framework of endodontics, a number of clinicians are using the concept of dentine tissue preservation in their clinical practice.

The first articles describing how to apply the minimally invasive concept to access cavity preparation were published by Clark and Khademi (2010a, 2010b). Amongst the several concepts introduced by the authors, the core aspect concentrates in maintaining the pulp chamber roof – the so-called soffit – and the pericervical dentine as much as possible in order to ultimately improve the tooth's survival. In their conceptual, but non-evidence-based narrative, the authors refutes the basic concepts of endodontics by using analogies such as *“this 360° soffit or roof-wall interface can also be compared with the metal ring that stabilizes a wooden barrel”* and also emphasize that *“research will certainly need to be done to validate the strength attributes of the roof strut or soffit”*.

In the following years, the popularity of minimal access cavities started to grow in social media networks, and other more radical design types such as “ninja” and truss, that aim to preserve the dentinal bridge between two or more small occlusal cavities prepared to access the root canal orifices of multi-rooted teeth, were also proposed without any scientific support. The rapid spread of these less invasive access cavities triggered the attention of researchers and clinicians and, four years after the Clark and Khademi proposal, its effect on the fracture resistance of teeth was tested experimentally for the first time. Krishan et al. (2014) evaluated the impact of access cavity size on the fracture resistance of incisors, premolars, and molars by combining a micro-computed tomographic (micro-CT) analysis with the conventional maximum load to failure approach. Although the authors found that the minimal access cavity conveyed some benefit in increasing the fracture resistance of teeth, it was also associated with the risk of compromising the quality of canal instrumentation.

Since then, several studies on this topic have been published, but with contradictory results (Silva et al., 2020c).

While some articles reported an improved resistance to fracture in teeth with minimally invasive access cavities (Abou-Elnaga et al., 2019; Makati et al., 2018; Marinescu et al., 2020; Plotino et al., 2017; Saberi et al., 2020; Santosh et al., 2021), the majority of studies failed to demonstrate such an effect (Augusto et al., 2020; Barbosa et al., 2020; Chlup et al., 2017; Corsentino et al., 2018; Ivanoff et al., 2017; Lima et al., 2021; Maske et al., 2021; Özyürek et al., 2017; Pereira et al., 2021; Roperto et al., 2019; Rover et al., 2017, 2020; Sabeti et al., 2018; Silva et al., 2020a, 2021b; Xia et al., 2020). Therefore, comparison of the benefits and harms between the minimally invasive and traditional access cavities remains debatable. This narrative review aims to discuss the advantages and limitations of methodologies used in these laboratory experiments and to discuss the present status and future directions of studies on minimal endodontic access cavities in endodontics.

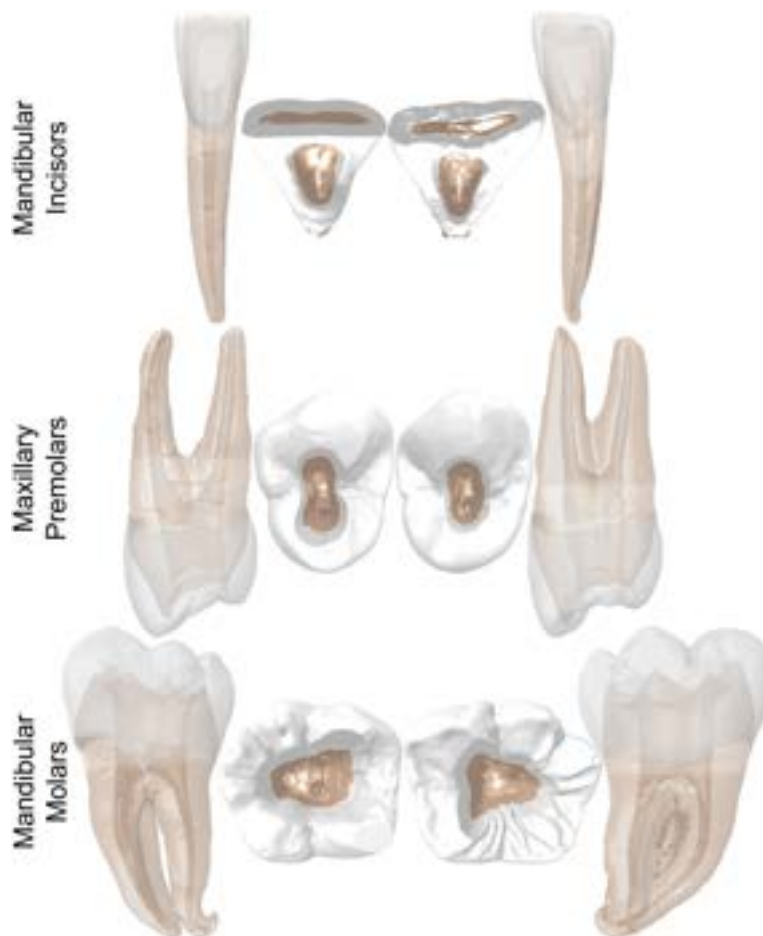
LITERATURE SEARCH STRATEGIES

This is a narrative review of the literature on the topic of minimally invasive access cavity preparation in endodontics. The search was conducted without parameter restrictions up to August 2021 by two independent evaluators using specific Medical Subject Heading (MeSH) terms and free descriptors in PubMed, Scopus, Web of Science, and ScienceDirect databases. After applying a combination of descriptive terms under Boolean operations, studies that evaluated the influence of minimally invasive access preparations on root canal treatment and on fracture resistance of teeth were selected. A complementary screening of the references and a manual search in the highest impact journals in endodontics, namely, the International Endodontic Journal and Journal of Endodontics were also accomplished. After this initial screening, the full text of the relevant articles was read, and their main ideas extracted and discussed. The final selection comprised papers that compared various types of minimally invasive access cavity preparations in terms of fracture resistance of teeth, stress distributions through finite element models, and their influence on different stages of root canal treatment.

TRADITIONAL ACCESS CAVITY PREPARATION

Access cavity preparation is defined as *“the opening prepared in a tooth to gain entrance to the root canal*

FIGURE 1 Schematic images showing incisal/occlusal and sagittal views (translucent images) of two mandibular incisors, two maxillary premolars, and two mandibular molars with TradAC



system for the purpose of cleaning, shaping, and obturating” (AAE, 2020). It is the foremost technical step of root canal treatment requiring extensive knowledge of the internal and external anatomy of the teeth (Christie & Thompson, 1994; Rover et al., 2017; Yahata et al., 2017). Moreover, if poorly executed, the location, negotiation, debridement, disinfection, and filling of root canals can be seriously compromised (Christie & Thompson, 1994; Costa et al., 2019; Rudolph et al., 1957). One of the first descriptions of the traditional access cavity design was written almost 100 years ago by Crane (1920). According to him “[...] and the coronal cavity so shaped that free direct access may be had to each canal in a line with its long axis. [...] Wherever possible, the natural walls of the pulp chamber should be preserved as these will guide the broach naturally into the canals. The best method is to enlarge the cavity of access until the root of the pulp chamber consists of only a thin layer of dentin and then remove this with chisels and hoes”.

Notwithstanding that the overall access preparation design had been established several decades ago, the traditional designs of access cavity were consistently described only in 1965 by John Ingle in the first edition of his textbook (Ingle, 1965). In fact, Ingle adapted to endodontics

the concept of cavity preparation as proposed by Black (1908), which comprises methodical operative sequence stages, including specific outline form, convenience form, cavity toilet, retention form, resistance form, and extension for prevention. For the matter of the present review, the most important aspects to be discussed are the convenience form and extension for prevention. The convenience form should provide a direct access to the apical foramen by extending the lateral walls of the cavity, thus removing all intervening dentine, while the extension for prevention aimed to enlarge the root canal in all dimensions to achieve the convenience form and prevent complications (Ingle, 1965). In general, the traditional access cavity preparation can be summarized in three key points: (i) complete unroofing of the pulp chamber with the exposure of the pulp horns, (ii) creation of a smooth unimpeded pathway to the root canal orifices, and (iii) preservation of sound structure of the tooth (Gutmann & Fan, 2016; Ingle, 1985; Korzen & Pulver, 1978; LaTurno & Zillich, 1985; Levin, 1967; Wilcox & Walton, 1987; Wilcox et al., 1989) (Figure 1).

Pre-designed outline forms of the traditional endodontic access cavity have remained practically unchanged for decades mostly due to technical limitations related to the endodontic armamentarium. Consequently,

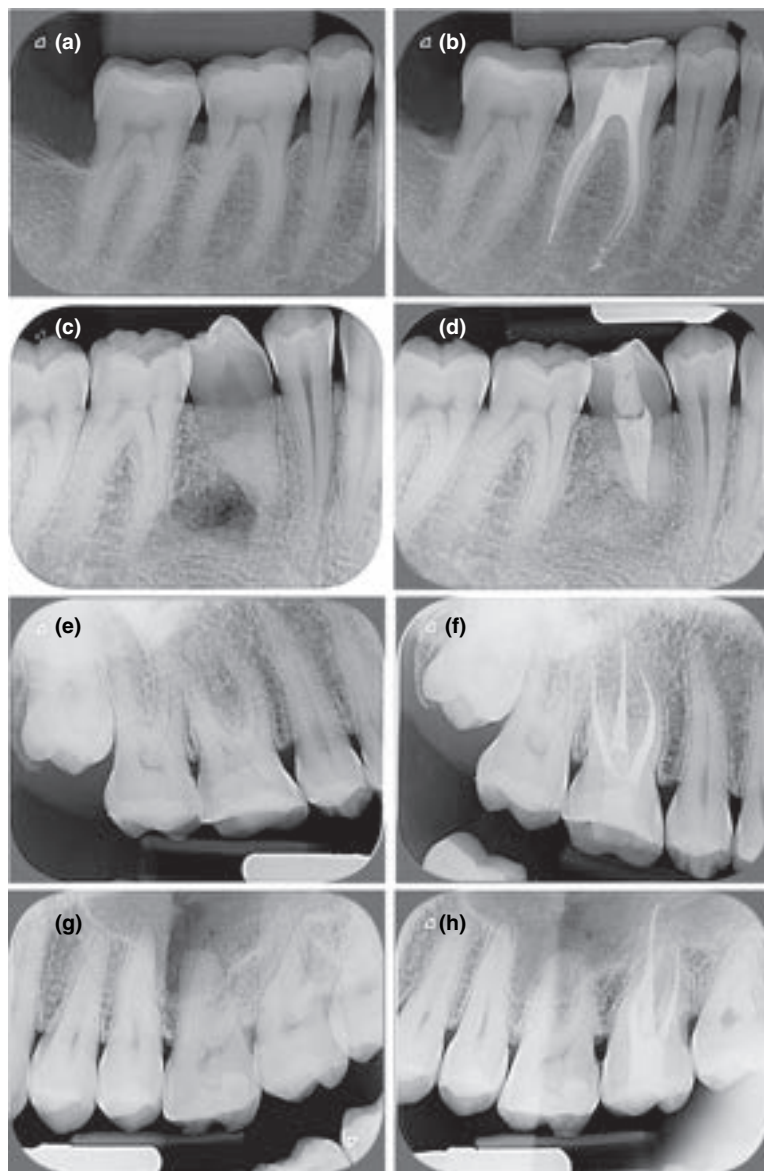


FIGURE 2 Root canal treatment of different teeth performed with technological development, such as ultra-flexible instruments, visual magnification, superior illumination, enhanced root canal irrigation systems, and ultrasonic tips. (a and b) Mandibular right first molar (1-year follow-up); (c and d) Mandibular right second pre-molar (2-year follow up); (e and f) Maxillary right first molar (2-year follow up); (g and h) Maxillary left second molar (3-year follow up). It is important to state that while access cavities with dentine preservation were obtained, the biological and technical basis of root canal treatment was not neglected (Courtesy of Dr. Mario Zuolo)

straight-line access to the root canals with smooth and divergent walls used to be recommended to improve the visualization of root canal orifices and avoid procedural complications, such as root canal transportation (Alovisi et al., 2018; Rover et al., 2017), instrument fracture (Silva et al., 2021a), and missed root canals (Costa et al., 2019; Rover et al., 2017). In the last two decades, however, considerable technological advancements took place in several aspects of endodontic treatment, including in instruments (metallurgy, design, and kinematics), imaging (cone-beam computed tomography), optics (operating microscope with high illumination), ultrasonics, and supplementary irrigation devices. Taken together, these technological advances make it possible to perform access cavities with reduced sizes, the so-called minimally invasive or contracted access cavities, without neglecting the technical and biological basis of root canal treatment (Bóveda & Kishen, 2015) (Figure 2).

MINIMALLY INVASIVE CONCEPT: DENTINE PRESERVATION

In endodontics, the trend towards dentine conservation began with two opinion-based publications from Clark and Khademi (2010a, 2010b). In these articles, the authors focused on the impact of the traditional access cavity preparation on the long-term outcome of root-filled teeth. By stating that “*the traditional approach to endodontic access is fundamentally flawed*”, Clark and Khademi (2010a) strived to deconstruct the classical principles of access cavity preparation: the complete unroofing of the pulp chamber and the straight-line access to root canals. Instead, they proposed a new cavity design aiming to maintain as much as possible of the pulp chamber roof and the so-called pericervical dentine, an area located 4 mm above and below the crestal bone, which theoretically is responsible for the transmission and balance of occlusal forces

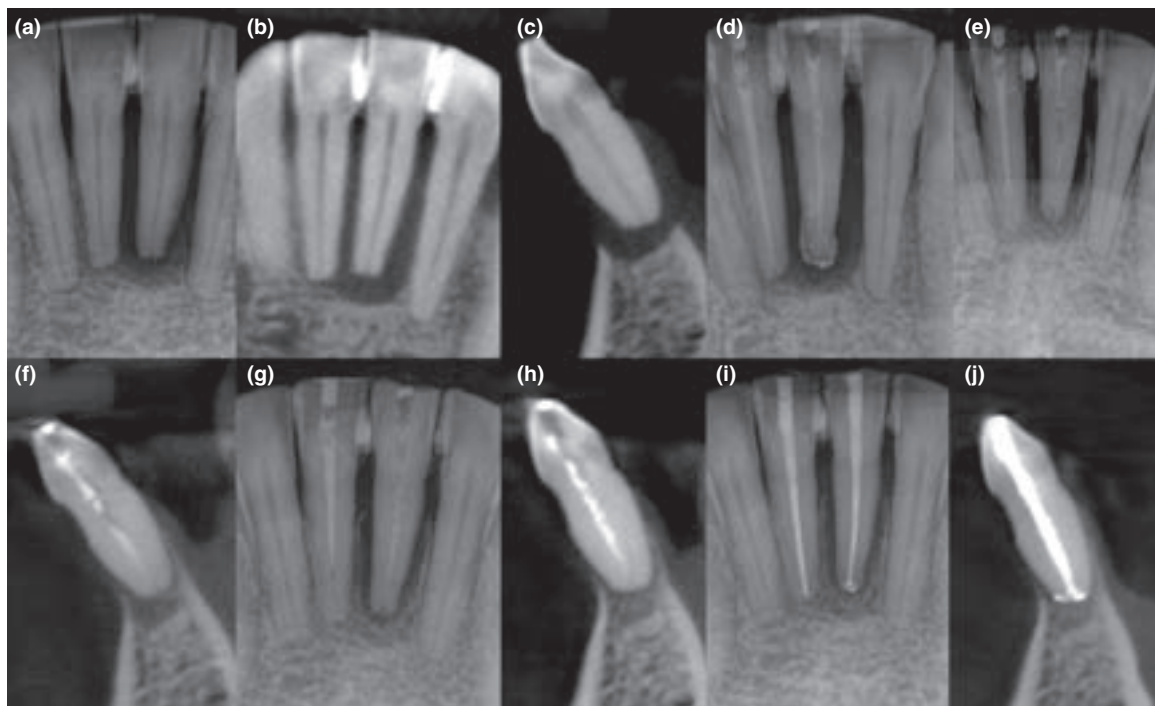


FIGURE 3 Mandibular incisor with apical periodontitis and massive bone loss referred for root canal treatment. (a–c) Preoperative radiographic and tomographic images (January 2020). (d) Intracanal medication after preparation procedures performed through a conservative access cavity (January 2020). (e–f) Radiographic and tomographic images after (e–f) 8 and (g–h) 13 months showing the bone repair progression. (i–j) Immediate post-operative radiographic and tomographic images demonstrating the complete bone repair after 18 months from the initial procedures (Courtesy of Dr. Carlos Bóveda)

to the root (Bóveda & Kishen, 2015; Clark & Khademi, 2010a; Gluskin et al., 2014). According to their rationale, the safest way to avoid damaging this structure is through partial preservation of the pulp chamber roof, which would reduce the flexion of the cusps (Clark & Khademi, 2010a). Diverging from the main principles of the traditional approach, minimal access cavities are reasoned on particular geometrical shapes that prioritize the removal of restorative material ahead of tooth structure, enamel ahead of dentin, and occlusal tooth structure ahead of the cervical dentine, which is only possible with the assistance of cutting-edge technologies (Bóveda & Kishen, 2015) (Figures 3, 4 and 5). Worthy of attention is the fact that the concepts of Clark and Khademi (2010a) were not proposed with scientific evidence but were based solely on their own assumption that retaining the *soffit* and preserving as much as possible of the pericervical dentine would avoid a decrease in the fracture resistance strength of root-filled teeth.

ACCESS CAVITY NOMENCLATURE: MISMATCHING OF TERMS

Terminology can be defined as a system of terms used in a given scientific field, whereas nomenclature is a

normalized system of exactly defined terms arranged according to certain classification principles (Kachlik et al., 2008). Terminological consistency in science is important to communicate ideas and explain ideas unambiguously. One of the greatest problems in many fields of science and knowledge, including endodontics, is the multiplicity of names and definitions given to a diagnostic procedure, anatomical structure, or technique, which preclude the development of a sound basis for proper scientific communication. The proposal for different access cavity designs is a relatively new trend in endodontics, and the numerous abbreviations proposed in the literature are characterized by mismatching and overlapping terms, leading to challenges around comprehension and readability of the articles (Silva et al., 2020c).

Although all types of minimal invasive access preparations can be referred to as contracted cavities (Bóveda & Kishen, 2015), 40 different terms have been proposed to define them, most having the same meaning, but allocated different acronyms (Table 1). The first attempt to standardize the different types of access cavity preparation was done by Isufi et al. (2020) whose rationale claimed that the nomenclature should follow the volume of the dentine and enamel removed during access preparation. In this way, ultraconservative, conservative, and traditional endodontic access cavities would be characterized

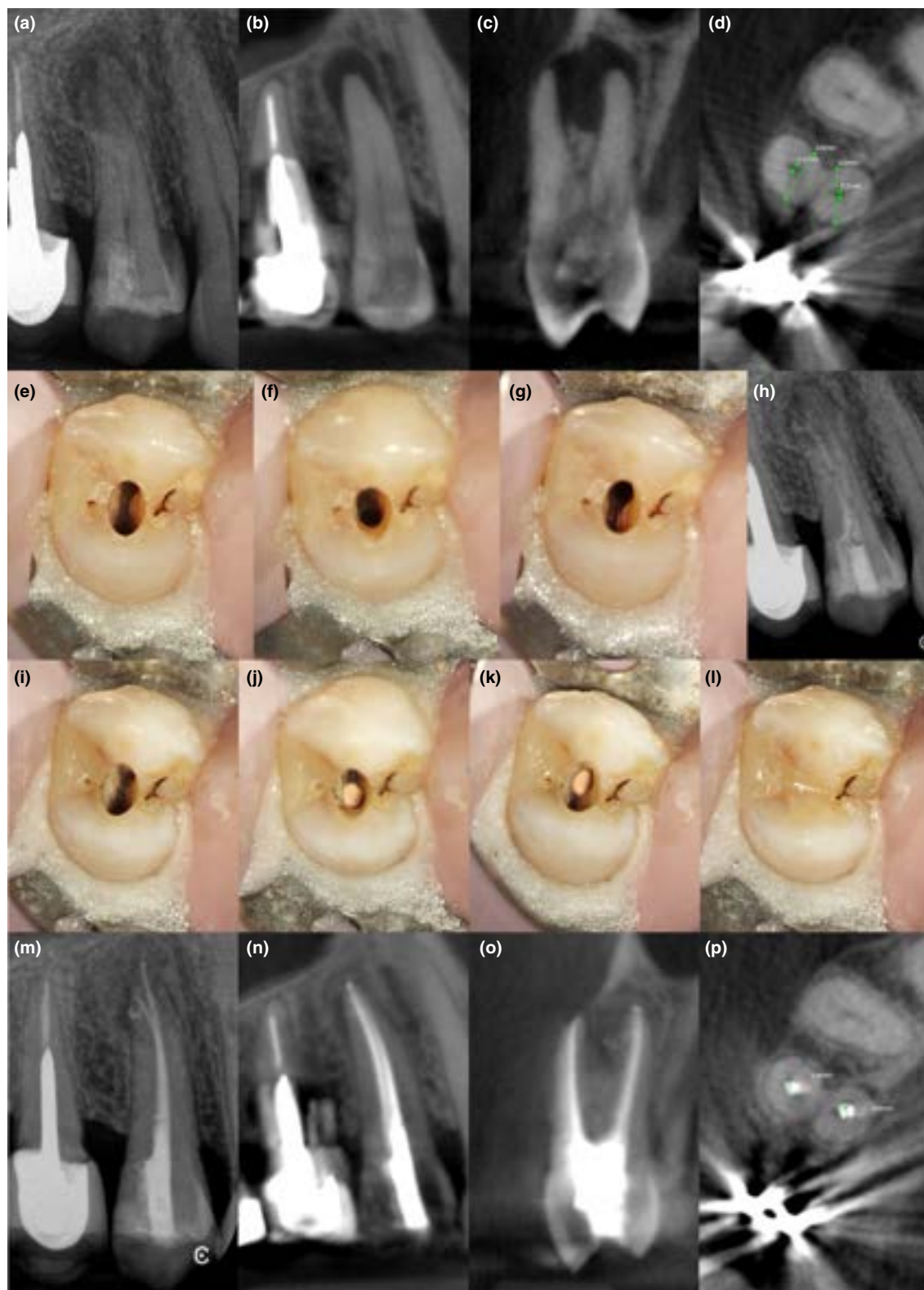


FIGURE 4 (a–d) Preoperative radiographic and tomographic images of a maxillary first right premolar with apical periodontitis referred for root canal treatment. (e–g) Root canal preparation and disinfection through a conservative access cavity preparation. (h) Intracanal medication after 6 months showing bone repair. (i–l) Occlusal view of the tooth after filling procedures. (m–p) Radiographic and tomographic images after 4 years of filling procedures demonstrating bone repair (Courtesy of Dr. Carlos Bóveda)



FIGURE 5 (a–d) Preoperative radiographic and tomographic images of a maxillary first right molar referred for root canal treatment. (e–f) Occlusal view of the tooth showing the conservative access cavity preparation. (g–j) Immediate postoperative radiographic and tomographic images of the tooth after filling procedures. (k) 4-year follow-up (Courtesy of Dr. Carlos Bóveda)

when the volume of the removed dentine and enamel in premolars and molars were $\leq 6\%$, from 6 to 15%, or $\geq 15\%$, respectively (Figures 6 and 7). This classification, however, has a significant limitation. In their study, for example, the access cavity preparation in a mandibular molar was visually classified as conservative, but the volume of the dentine and enamel removed was 3.9%, which clearly characterized it as ultraconservative, according to their proposal. In another tooth, the access cavity in a maxillary premolar was classified as conservative, but the volume of the dentine and enamel removed (17.7%) was compatible with the traditional access type. Thus, a classification system based solely on the volume of hard tissue removed

is not appropriate. Even so, the study of Isufi et al. (2020) was important as it drew attention to the importance of measuring the volume of the hard tissues removed in laboratory studies.

Shabbir et al. (2021) proposed a broader classification including anterior and posterior teeth as well as addressing type of access designs not previously mentioned by Isufi et al. (2020) (Figures 8, 9 and 10). Even though it represents an advance in the classification of access cavities, the proposed acronyms are not intuitive or easy to understand (such as LAC, FAC, and IAC), and some of them have been used previously by other authors with different meanings, such as CEA, which may stand for either

TABLE 1 Abbreviations and terms proposed in the literature to classify the different types of access cavity geometries in endodontics

Abbreviation	Meaning	References
CA	Conventional access	Marinescu et al. (2020)
CAC	Conservative access cavity	Sabeti et al. (2018); Freitas et al. (2021)*; Mendes et al. (2020)
CariesAC	Caries-driven access cavity	Silva et al. (2020c)
CC	Conservative cavity	Marinescu et al. (2020)
CEA	Contracted endodontic access	Bóveda and Kishen (2015)
CEA	Conventional endodontic access	Maske et al. (2021)
CEAC	Conservative endodontic access cavity	Saygili et al. (2018)
CEC	Conservative endodontic cavity	Alovisi et al. (2018); Barbosa et al. (2020); Blauhut and Sonntag (2020); Chlup et al. (2017); Corsentino et al. (2018); Isufi et al. (2020); Ivanoff et al. (2017); Jiang et al. (2018); Krishan et al. (2014); Makati et al. (2018); Moore et al. (2016); Mustafa et al. (2020); Niemi et al. (2016); Özyürek et al. (2018); Pereira et al. (2021); Plotino et al. (2017); Reddy et al. (2020); Roperto et al. (2019); Rover et al. (2017); Spicciarelli et al. (2020); Tüfenkci and Yilmaz (2020); Tüfenkci et al. (2020); Wang et al. (2020); Xia et al. (2020); Zhang et al. (2019)
CECDW	CEC with divergent walls	Roperto et al. (2019)
CON	Conservative access cavity	Elkholy et al. (2021); Saber et al. (2020)
ConsAC	Conservative access cavity	Silva et al. (2020c); Karobari et al. (2021); Santosh et al. (2021)
DDC	Orifice-directed dentin conservation access	Neelakantan et al. (2018)
EEC	Extended endodontic cavity	Jiang et al. (2018)
MEA	Minimally invasive endodontic access	Maske et al. (2021)
MEC	Modified endodontic cavity	Zhang et al. (2019)
MI	Minimally invasive	Eaton et al. (2015); Freitas et al. (2021)*; Lin et al. (2020); Rover et al. (2020); Yuan et al. (2016)
MS	Modified straight-line	Lin et al. (2020)
NC	Ninja cavity	Marinescu et al. (2020)
NEAC	Ninja endodontic access cavity	Guler (2020)
NEC	Ninja endodontic cavity	Plotino et al. (2017); Reddy et al. (2020)
PEAC	Point endodontic access cavity	Saygili et al. (2018)
RestoAC	Restorative-driven access cavity	Silva et al. (2020c)
SL	Straight-line	Yuan et al. (2016)
SLF	Straight-line furcation	Eaton et al. (2015)
SLR	Straight-line radicular	Eaton et al. (2015)
T	Traditional	Rover et al. (2020)
TA	Truss access cavity	Abou-Elnaga et al. (2019)
TAC	Traditional access cavity	Abou-Elnaga et al. (2019); Sabeti et al. (2018); Mendes et al. (2020)
TAC	Truss access cavity	Barbosa et al. (2020)
TEAC	Traditional endodontic access cavity	Saygili et al. (2018)
TEC	Traditional endodontic cavity	Alovisi et al. (2018); Augusto et al. (2020); Barbosa et al. (2020); Blauhut and Sonntag (2020); Chlup et al. (2017); Corsentino et al. (2018); Guler (2020); Isufi et al. (2020); Ivanoff et al. (2017); Jiang et al. (2018); Krishan et al. (2014); Makati et al. (2018); Moore et al. (2016); Mustafa et al. (2020); Neelakantan et al. (2018); Niemi et al. (2016); Özyürek et al. (2018); Plotino et al. (2017); Reddy et al. (2020); Roperto et al. (2019); Rover et al. (2017); Saberi et al. (2020); Silva et al. (2020a); Silva et al. (2020b); Spicciarelli et al. (2020); Tüfenkci and Yilmaz (2020); Tüfenkci et al. (2020); Xia et al. (2020); Zhang et al. (2019)

TABLE 1 (Continued)

Abbreviation	Meaning	References
TradAC	Traditional access cavity	Karobari et al. (2021); Lima et al. (2021); Santosh et al. (2021); Silva et al. (2020c); Silva et al. (2021a); Silva et al. (2021b)
TRD	Traditional access cavity	Elkholy et al. (2021); Saber et al. (2020)
TREC	Truss endodontic cavity	Corsentino et al. (2018); Saberi et al. (2020)
TrecAC	Truss endodontic access cavity	Santosh et al. (2021)
TrussAC	Truss access cavity	Karobari et al. (2021); Silva et al. (2020c)
TS	Traditional straight-line	Lin et al. (2020)
TUS	Ultraconservative truss access cavity	Elkholy et al. (2021); Saber et al. (2020)
UEC	Ultraconservative endodontic cavity	Augusto et al. (2020); Isufi et al. (2020); Silva et al. (2020a); Silva et al. (2020b)
UltraAC	Ultraconservative access cavity	Lima et al. (2021); Silva et al. (2020c); Silva et al. (2021a); Silva et al. (2021b)

*Freitas et al., 2021 did not use abbreviations.

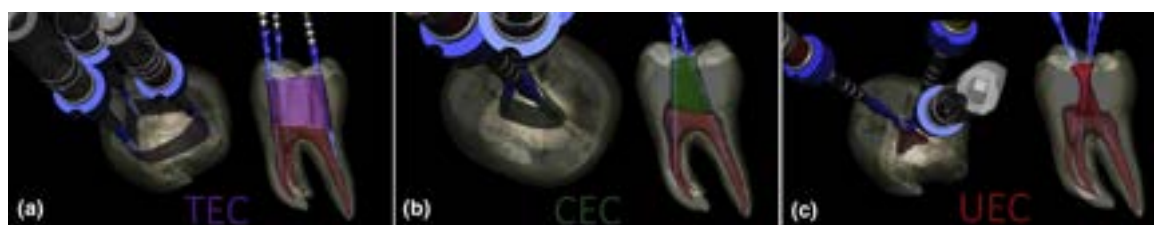


FIGURE 6 Isufi et al. (2020) classification based on the volume of dentine and enamel removed during access cavity preparation. A representative 3D reconstruction of the three different types of access cavities designed with the aid of 3D reconstruction software from CBCT data of scanned teeth and with real dimensional endodontic files in a mandibular molar in the occlusal and lingual views. (a) Traditional endodontic cavities (TECs) in cases of dentine and enamel removal are higher than 15% (*purple*), (b) the conservative endodontic cavities (CECs), in cases of removal up to 15% (*green*), and (c) the ultraconservative endodontic cavities (UECs), when the volume of dentine and enamel removed is equal or smaller than 6% (*red*) (Reprinted with permission)

contracted (Bóveda & Kishen, 2015) or conventional (Maske et al., 2021) access or DNA classically used to represent the deoxyribonucleic acid (Table 1). Besides, they included computer-assisted preparation in their classification which seems inappropriate considering that static or dynamic guided access are technical procedures in which the final access design will usually fall into some type of minimal access cavity.

A new terminology and uniformization proposal

Silva et al. (2020c) proposed a new classification by consolidating the different terminology related to access cavity geometries into eight categories in order to provide a common language and self-explanatory abbreviations (Figures 11 and 12):

- **Traditional Access Cavity (TradAC):** in posterior teeth, complete removal of the pulp chamber roof is followed by achieving straight-line access to the canal orifices, with smoothly divergent axial walls, so that all orifices

can be seen within the outline form (Figure 11). In anterior teeth, the straight-line access is obtained by removing the pulp chamber roof, the pulp horns, the lingual shoulder of the dentine, and further extending the access cavity to the incisal edge (Figure 12) (Levin, 1967).

- **Conservative Access Cavity (ConsAC):** in posterior teeth, preparation usually starts at the central fossa of the occlusal surface and extends with smoothly convergent axial walls to the occlusal surface, only as far as necessary to detect the canal orifices, preserving part of the pulp chamber roof (Clark & Khademi, 2010a, 2010b) (Figure 11). This access type can also be performed with divergent walls (ConsAC.DW) (Roperto et al., 2019) (Figure 11). In anterior teeth, it involves moving the entry point away from the cingulum towards the incisal edge on the lingual or palatal surface by creating a small triangular-shape or oval-shape cavity, conserving the pulp horns and the maximum pericervical dentine (Figure 12) (Vieira et al., 2020).
- **Ultra-Conservative Access Cavity (UltraAC):** known as “ninja” access, such cavities start out as described in the

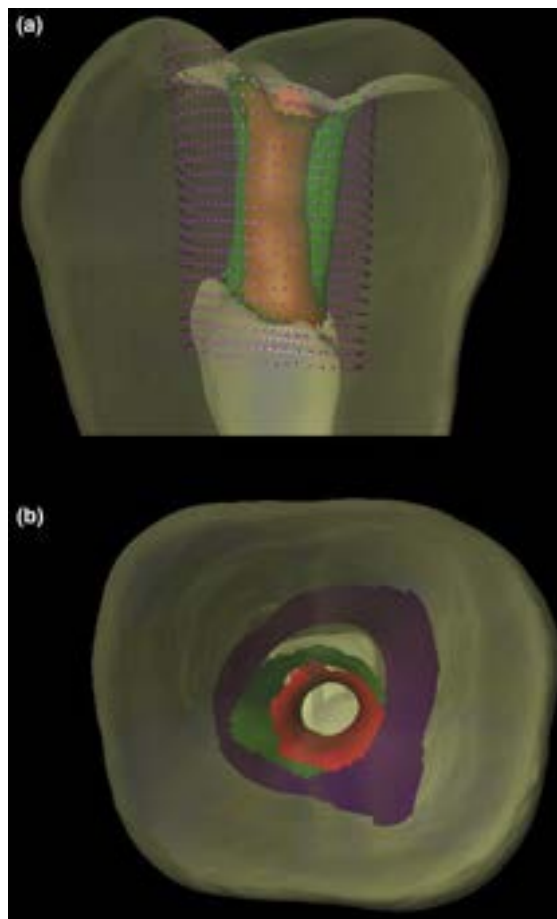


FIGURE 7 Representative 3D reconstruction of the superimposition of the three different types of access cavities prepared in a mandibular molar in the (a) lateral and (b) occlusal views. The TEC is shown in *purple*, the CEC in *green*, and the UEC in *red* (Reprinted with permission)

ConsAC, but with no further extensions, maintaining as much of the pulp chamber roof as possible (Plotino et al., 2017) (Figure 11). In anterior teeth, when there is attrition or a deep concavity in the lingual aspect of the crown, the access can be performed in the middle of the incisal edge, parallel to the long axis of the tooth (UltraAC.Inc) (Figure 12).

- **Truss Access Cavity (TrussAC):** aims to preserve the dentinal bridge between two or more small cavities prepared to access the canal orifice(s) in each root of multi-rooted teeth. In mandibular molars, for example, two or three individual cavities can be created to access the mesial and distal canals (Neelakantan et al., 2018) (Figure 11).
- **Caries-Driven Access Cavity (CariesAC):** access to the pulp chamber is performed by removing caries and preserving all remaining tooth structures (Figures 11 and 12), including the *soffit* structure, described as the underside of an architectural feature, such as the ceiling, the corner of the ceiling, and the wall (Clark et al., 2013).

- **Restorative-Driven Access Cavity (RestoAC):** in restored teeth with no caries, access to the pulp chamber is performed by totally or partially removing existing restorations and by preserving all possible remaining tooth structures (Figures 11 and 12).

GUIDED ACCESS CAVITY

Guided endodontics involves merging a CBCT imaging and surface scan of the tooth to create a guide (static navigation) (Buchgreitz et al., 2019a) or track a surgical instrument in real time and constantly visualizing its position (dynamic navigation) in order to create a drill path into the tooth (Moreno-Rabié et al., 2020) or design a path to reach the apical portion of the root (Fan et al., 2019). Byun et al. (2015) and Zubizarreta Macho et al. (2015) were the first to describe the endodontic treatment of anomalous teeth by planning the access cavity preparation using a guided implant placement software and custom-made guide jigs *via* the 3D printing technique. In the next year, some authors reported this technique as a valuable tool for the negotiation of partially or completely calcified root canals (Buchgreitz et al., 2016; van der Meer et al., 2016; Zehnder et al., 2016). Since then, the clinical applicability of guided endodontic procedures has been investigated in several studies focusing on static protocols using a 3D-printed template with an incorporated sleeve to guide the bur, while more recently, the use of dynamic navigation systems—a marker-camera-computer system for real-time guidance—has also been applied.

Static-guided technique

Static guidance (SG) refers to the use of a fixed surgical stent, which is made using computer-aided design/computer-assisted manufacture (CAD/CAM), based on a preoperative CBCT scan (Chong et al., 2019). In endodontics, CBCT data and 3D surface scan of the teeth can be superimposed using a dedicated software. By generating a virtual model of the tooth to be treated, the software helps create the virtual image of a drilling bur of specific dimensions. The virtual bur, superimposed on the targeted tooth, can be manually angled to create a straight-line access to a predetermined part of the root canal. After planning the orientation of the endodontic bur, a virtual template is designed in the software package and exported to the 3D printer in standard tessellation language (STL) format. Then, the physical model of the drilling guide can be used for access preparation (Nayak et al., 2018) (Figures 13 and 14).

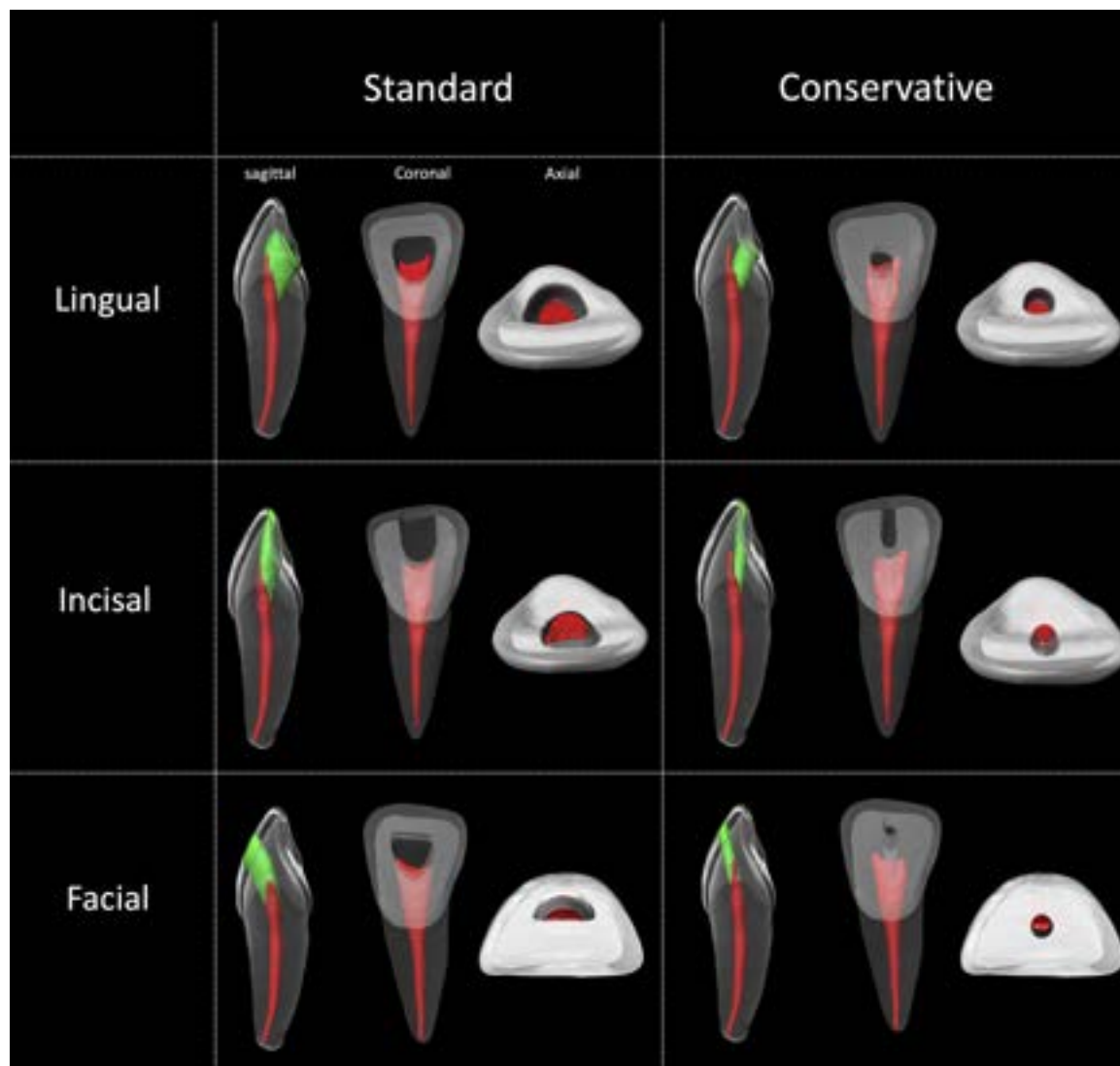


FIGURE 8 Shabbir et al. (2021) classification of anterior teeth. Micro-CT illustration of a maxillary central incisor showing lingual, incisal, and facial access cavity preparations in standard and conservative manners. The access is presented from the sagittal, coronal, and axial views. The green area represents the tooth structure removed during access preparation (Reprinted with permission)

A laboratory analysis of the computed-drill path based on a human tooth model was reported before the concept was introduced in clinical practice, and it was revealed that its accuracy was sufficient to reach a predefined target point when using the guide (Buchgreitz et al., 2016). Although the measuring methods reported in the *ex vivo* studies are heterogeneous, the accuracy of SG access cavity preparations has been reported to be reliable (Connert et al., 2017; Moreno-Rabié et al., 2020; Zehnder et al., 2016). Static surgical guides can be tooth-, mucosa-, or bone-supported (Chong et al., 2019) and commonly include a sleeve (metallic or plastic) that is used to guide the bur during the drilling procedure (Moreno-Rabié et al., 2020). This type of guide, however, requires the use of a dedicated bur with 34–37 mm in length that fits inside the sleeve, the sleeve to be positioned exactly over the tooth to be treated, and a sleeve with a minimum of 5 mm in

length to reduce the risk of deviation. As a consequence, it reduces the accessibility in posterior teeth because of the limited space, blocks the clinician's vision, and compromises water cooling (Torres et al., 2021b). Recently, a novel SG endodontic technique using a sleeveless 3D printed guide on the basis of CBCT data was proposed to solve the problem of lack of vertical space, allowing work in the posterior areas with improved visibility and irrigation during drilling (Torres et al., 2021b).

According to several authors, the SG approach offers a highly predictable alternative to access the root canals in comparison to freehand drilling in challenging cases (Ali & Arslan, 2021; Buchgreitz et al., 2016, 2019a, 2019b; Byun et al., 2015; Casadei et al., 2020; Connert et al., 2017, 2018, 2019; Kostunov et al., 2021; Krastl et al., 2016; Krug et al., 2020; Lara-Mendes et al., 2018a, 2018b; Llaquet Pujol et al., 2021; Loureiro et al., 2020; Maia et al., 2019; Shi et al., 2018;

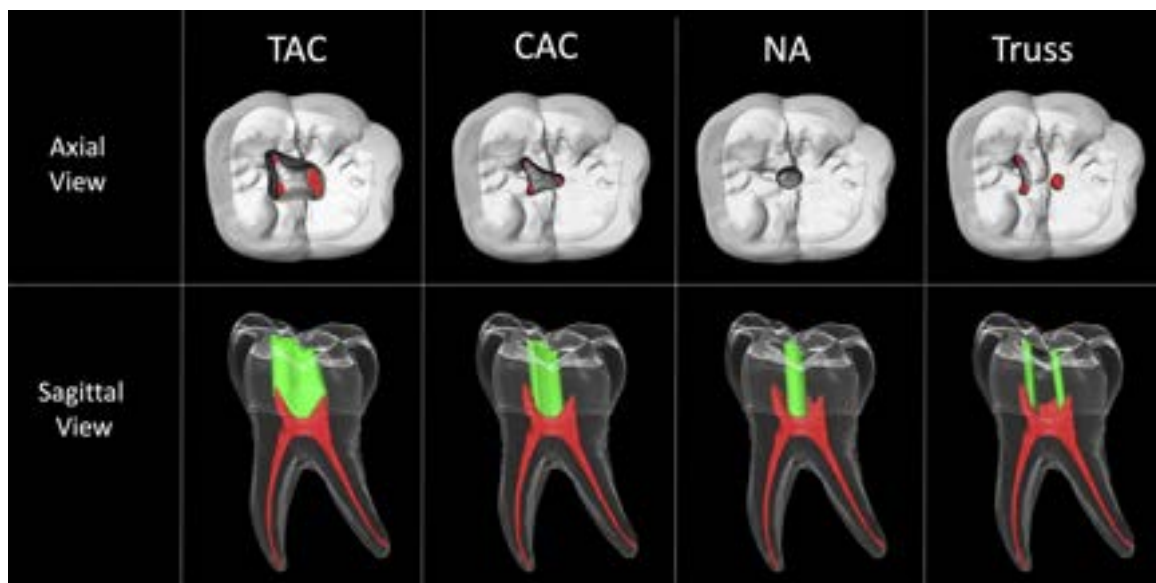


FIGURE 9 Shabbir et al. (2021) classification of posterior teeth. Micro-CT illustration of a mandibular first molar showing traditional, conservative, and ultraconservative access cavity preparations. The access is presented from the occlusal and buccal views. The *green area* represents the tooth structure removed during access preparation (Reprinted with permission)

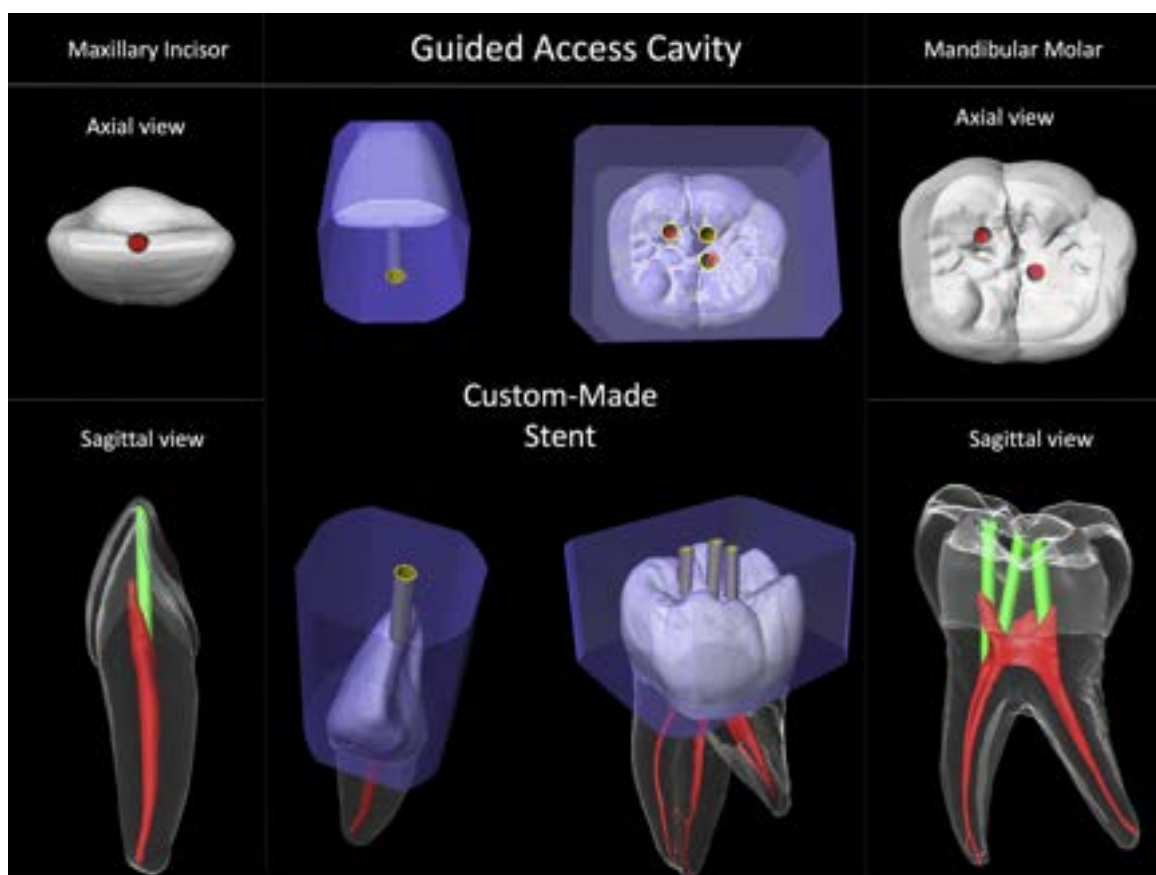


FIGURE 10 Shabbir et al. (2021) classification for guided access cavities. An illustration of guided access cavities preparation performed on a maxillary central incisor and a mandibular first molar. The *green area* represents the tooth structure removed during access preparation (Reprinted with permission)

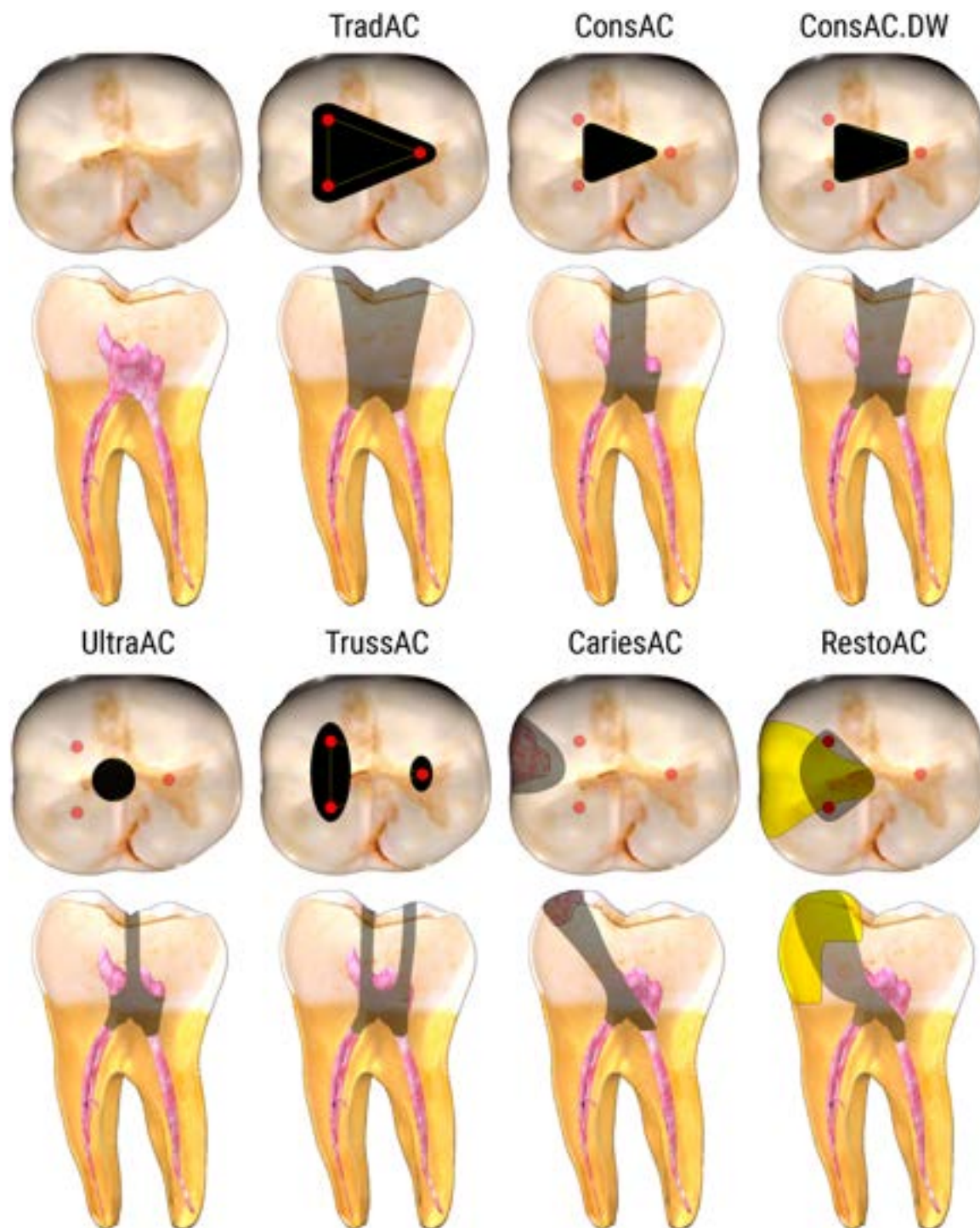


FIGURE 11 Silva et al. (2020) classification of the access cavity designs in posterior teeth. Traditional access cavity (TradAC); conservative access cavity (ConsAC); conservative access cavity with divergent walls (ConsAC.DW); ultra-conservative access cavity (UltraAC); truss access cavity (TrussAC); caries-driven access cavity (CariesAC); and restorative-driven access cavity (RestoAC)

Tchorz et al., 2019; Todd et al., 2021; Torres et al., 2019, 2021b; Zehnder et al., 2016). However, the application of SG for endodontic access may be burdened with multiple sources of errors during the workflow because of an inadequate intraoral scan or impression, CBCT artefacts, human error during the design leading to poor alignment during meshing of digital

and CBCT renderings, and inconsistency in resin thickness during 3D printing, which ultimately may cause instability of the guide (Jain et al., 2020b) (Table 2). The introduction of recently developed technology referred to as trace registration or dynamic-guided navigation has eliminated several drawbacks related to SG preparation.

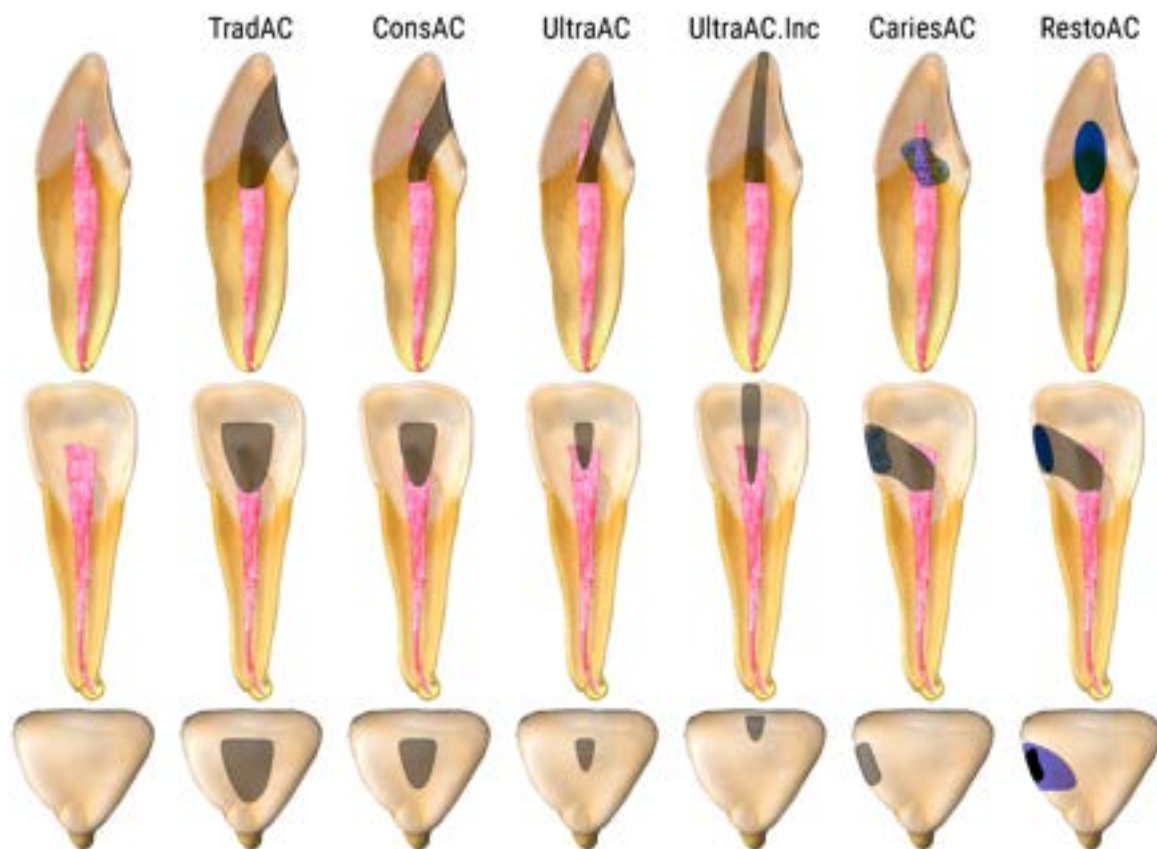


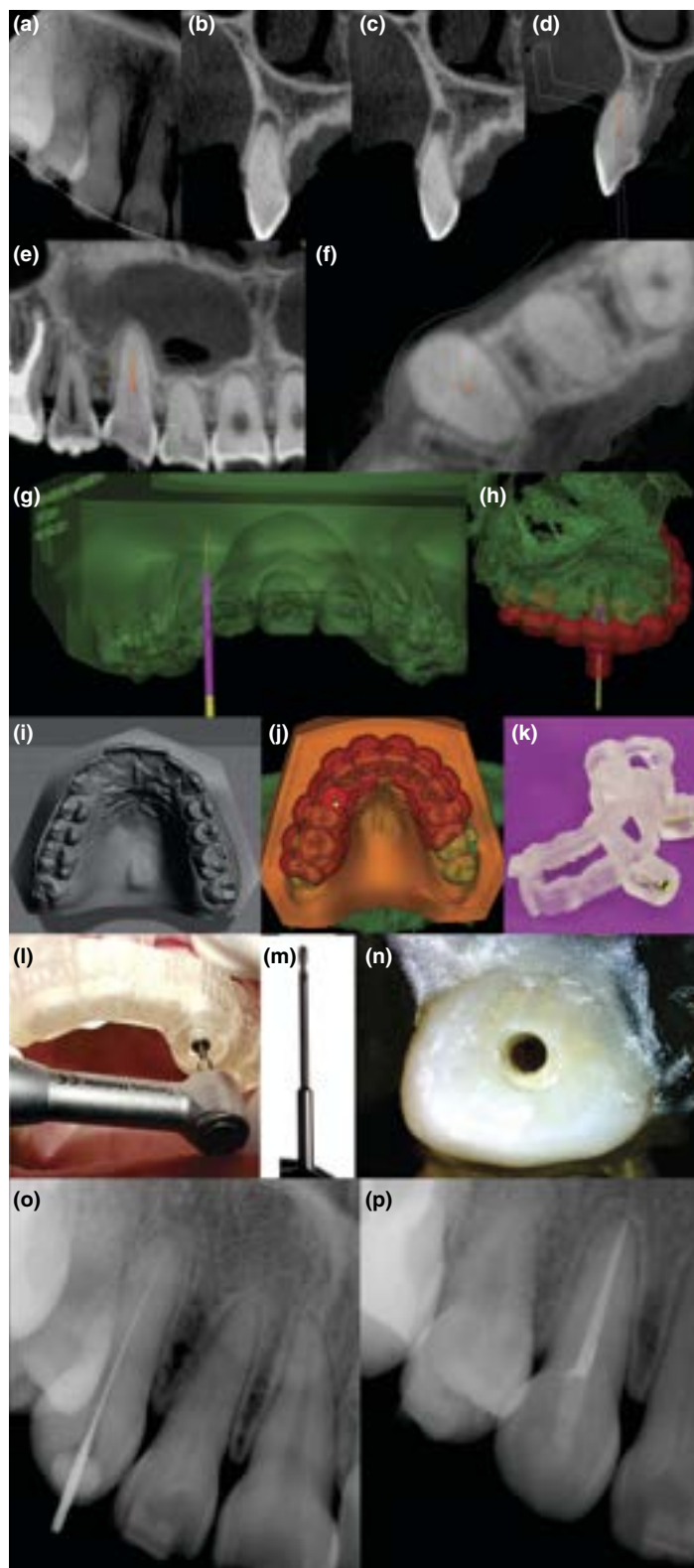
FIGURE 12 Silva et al. (2020) classification of the access cavity designs in anterior teeth. Traditional access cavity (TradAC); conservative access cavity (ConsAC); ultra-conservative access cavity (UltraAC); ultra-conservative access cavity performed in the incisal edge (UltraAC. Inc); caries-driven access cavity (CariesAC); and restorative-driven access cavity (RestoAC)

Dynamic-guided technique

The dynamic-guided technique, also known as dynamic navigation system (DNS), is based on computer-aided surgical navigation technology and is analogous to global positioning systems or satellite navigation (Stefanelli et al., 2019) being firstly introduced in dentistry to improve the insertion accuracy of dental implants (Block & Emery, 2016; Block et al., 2017; Chen et al., 2018; Chong et al., 2019; Stefanelli et al., 2019). Recently, DNS with passive optical technology was applied to endodontics (Chong et al., 2019; Connert et al., 2021; Dianat et al., 2020, 2021; Gambarini et al., 2020; Jain et al., 2020a, 2020b; Torres et al., 2021a). This technology allows the use of a computer to guide special burs in real-time based on information gathered from a CBCT image. Motion tracking enables the system by following the position of both the patient and the dental handpiece throughout the procedure. The ideal drill position is planned virtually by the surgeon using the CBCT data set uploaded into the planning software. Sensors attached to the surgical handpiece and the patient's head or teeth transfer the 3D spatial information to a stereo tracker (Dianat et al., 2020, 2021) (Figures 15, 16 and 17).

According to Buchanan (2018), Dr Charles Maupin was the first dentist to use a dynamic guidance system designed only for implant surgery to cut access cavities in calcified teeth back in 2016. Using the same protocol, Buchanan (2018) reported the use of DNS in three clinical cases and concluded that this technique was very effective in locating canals and creating less-invasive access preparations. In the next year, Burgess (2019) and Nahmias (2019) also published case reports showing the potential of the DNS on locating and treating calcified canals by monitoring the access preparation pathway three dimensionally and providing guidance through the calcified portion of the tooth to accurately locate the root canals. These initial impressions were further confirmed by experimental studies testing its accuracy (Chong et al., 2019; Connert et al., 2021; Dianat et al., 2020, 2021; Gambarini et al., 2020; Jain et al., 2020a, 2020b; Torres et al., 2021a). These authors reported several advantages of the DNS technique over traditional techniques, which are very complex, skill-dependent, and time consuming. However, the high cost can still be considered one of its major drawbacks (Table 3). Besides, when comparing the accuracy results to that of static guide systems, the values seem slightly high (Moreno-Rabié et al., 2020) and, for this reason, comparison studies

FIGURE 13 (a–d) Radiographic aspects of a maxillary canine with pulp canal obliteration; (e–j) Digital planning of a static guide using CBCT and oral scanning. After merging the images, a virtual copy of the drill used for the access preparation was superimposed on the root canals; (k) Printed guide; (l) Drilling the root canal; (m) Bur used to drill the root canal; (n) Clinical aspect after guided-access preparation; (o) Radiographic image showing a size 10 K-file in the located root canal; (p) Radiographic image showing the filled root canal (Courtesy of Dr. Lucas Moreira Maia)



that assess both techniques are still required (Torres et al., 2021a).

In relation to access cavity preparation, Gambarini et al. (2020) were only authors thus far that evaluated the use of the DNS to prepare ultra-conservative access cavities using artificial replicas of teeth. According to

them, although more preoperative preparations along with additional CBCT scans were needed, the DNS technology was significantly more precise, showing smaller mean values in the angulation (4.8°) and in the maximum distance from the ideal position (0.34 mm), when compared to free-hand preparation (mean values were

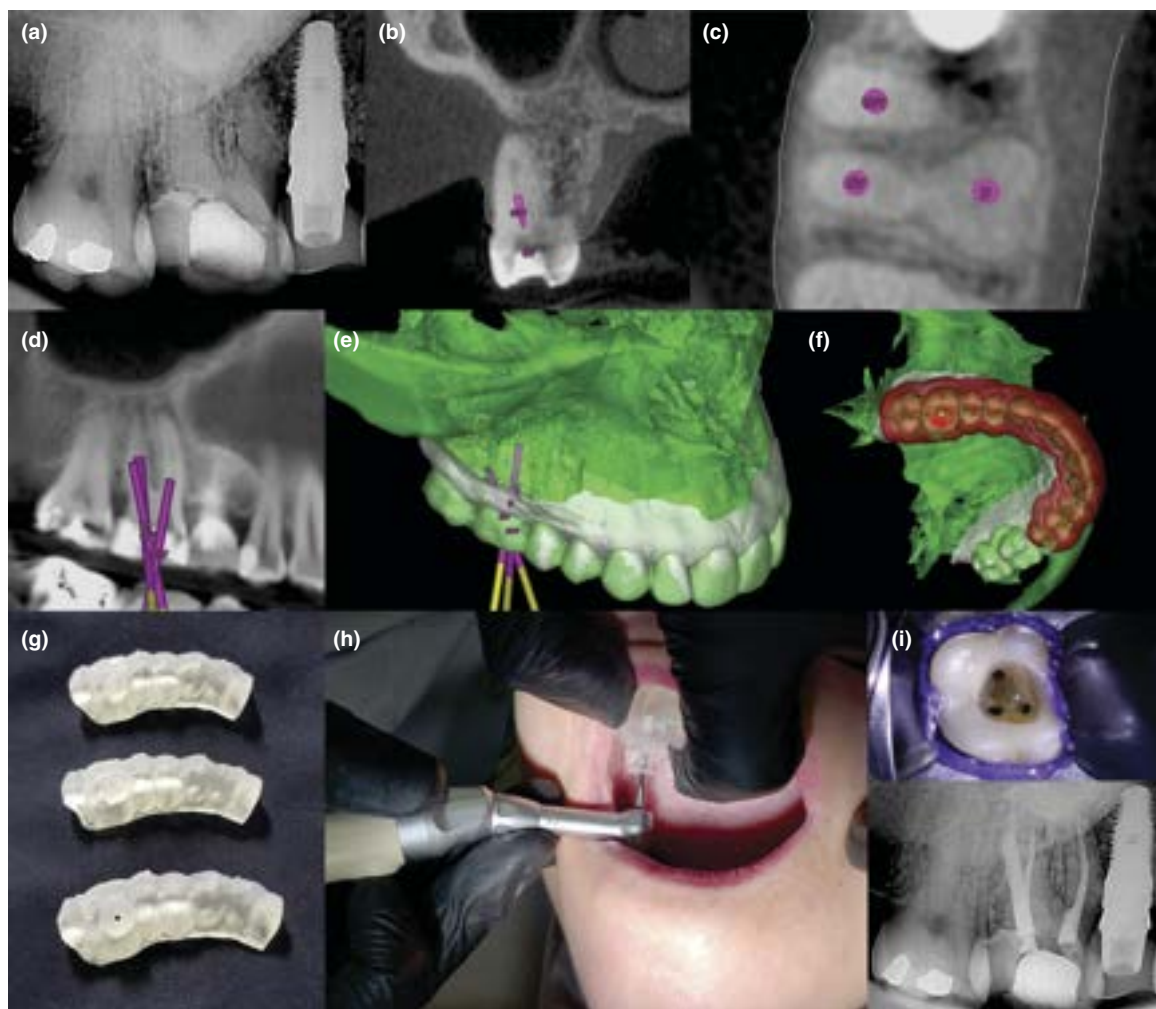


FIGURE 14 (a) Radiographic aspects of a maxillary first molar with pulp canal obliteration in all root canals. Previous access attempts were performed by two experienced endodontists, but without root canal location; (b–f) Digital planning of a static guide using CBCT and oral scanning. After merging the images, a virtual copy of the drill used for the access preparation was superimposed on the root canals; (g) Printed guides for individually accessing the root canals (mesiobuccal, distobuccal, and palatal canals); (h) Drilling the root canals; (i) Clinical aspect after guided-access preparation showing the three accessed root canals; (f) Radiographic image showing the prepared and filled root canals (Courtesy of Dr. Warley Luciano Fonseca Tavares)

21.2° and 0.88 mm, respectively). The authors concluded that the use of DNS could increase the benefits of ultra-conservative access cavities by precisely planning any possible inclination of the drill while reaching the pulp chamber and canal orifices, without removing unnecessary dental tissues.

TOOLS FOR MINIMALLY INVASIVE ACCESS PREPARATION

The concept of minimally invasive access preparation aims to transform the cavity outline from the traditional operator-centric design to a strategy focused on dentine preservation. In this way, current technological developments embracing the use of ultra-flexible instruments, visual magnification, superior illumination, enhanced

root canal irrigation systems, thin ultrasonic tips, and three-dimensional imaging technology (CBCT) have made dentine conservation a feasible objective (Bóveda & Kishen, 2015).

Three-dimensional imaging technology (CBCT)

Over the last decades, technological advancements in three-dimensional computed tomographic imaging for diagnosis, such as CBCT, have given rise to more accurate research and clinical methods to be applied in endodontics. CBCT is the preferred imaging modality for complex situations demanding a more detailed localization and description of tooth anatomy because of its capacity to render 3D information compared to conventional

TABLE 2 Advantages and drawbacks of the Static-Guided Navigation (SG) in endodontics

Advantages	Drawbacks
- Reduced iatrogenic damage and complications to the tooth during a procedure of localizing partial or complete pulp canal obliteration (Buchgreitz et al., 2019a). - Decreased treatment time when compared to free-hand preparation (Ali & Arslan, 2021). The time spent performing the drill path was rough estimate to be less than 5 min (Buchgreitz et al., 2019a, 2019b). The extra time is not spent chairside at the dental office but takes place within the digital laboratory (Connert et al., 2017). - SG prevents perforations or canal transportation and stops when there is a reasonable chance to complete the instrumentation beyond the curvature (Buchgreitz et al., 2019a). - More predictable and expeditious location of calcified root canals with significantly less substance loss than the traditional endodontic access (Connert et al., 2021). - It is possible to perform complex procedures with less influence of the operator's experience than traditional access preparations (Connert et al., 2021).	- In a clinical setup, many teeth that require intervention have full coverage restorations. In this condition, CBCT artifacts resulting from highly radiopaque restorations may hamper the alignment of the scans (Ackerman et al. 2019; Ali & Arslan, 2021; Connert et al., 2021). - The first generation of the SG system requires additional CBCT scans with thermoplastic stents and radiographic fiducial markers, which increased the radiation dose (Chong et al., 2019). The actual trace registration system can use pre-existing small field of view CBCT scans, thereby reducing the amount of radiation exposure (Connert et al., 2018). - Superimposition of the optical impression may be more challenging when using a small field-of-view CBCT scan (Ackerman et al. 2019). - A printed guide has inherent thickness and can provide only one straight trajectory to the target which may pose difficulty in positioning the handpiece (Ackerman et al. 2019; Ali & Arslan, 2021; Chong et al., 2019; Connert et al., 2021). If the interocclusal space is not large enough for the guide, bur, and handpiece, template use can be limited in the posterior region (Connert et al., 2017, 2019). - This technique has anatomical limitations related to the canal curvature, the presence of radicular grooves, oval roots, or isthmuses (Buchgreitz et al., 2019b; Connert et al., 2017). - Since SG does not allow water cooling, the friction heat from the spiral bur can increase the temperature over the tooth during drilling (Ali & Arslan, 2021; Connert et al., 2017, 2018, 2019; Krastl et al., 2016; Torres et al., 2021b; Zehnder et al., 2016). - Because of its rigidity, once SG is manufactured, the template does not allow the clinician to adjust angulation, size, depth, or type of the bur during treatment (Chong et al., 2019; Connert et al., 2019). - Planning and manufacturing the template is time-consuming (Buchgreitz et al., 2019b; Connert et al., 2019) and costly (Connert et al., 2017). - In multi-rooted teeth, SG needs a number of different sleeves to permit access to individual canals (Chong et al., 2019; Lara-Mendes et al., 2018). - Forces generated particularly at the tip of the bur can increase and might induce dentinal microcracks (Connert et al., 2018; Krastl et al., 2016). - The loss of hard tissue is comparable to a post-space preparation and may impair the stability of the root, thereby making the tooth more prone to fracture (Krastl et al., 2016). - SG guides must be positioned over several teeth to acquire proper stability. Therefore, it is necessary to isolate several teeth or start treatment without the rubber dam (van der Meer et al., 2016).

dental radiographs (AAE/AAOMR, 2015). In the concept of minimally invasive endodontics, data from CBCT images can be used to obtain a detailed identification of the root canal system, its variations, and anomalies; the position and size of the pulp chamber; the presence of calcifications; the number, position, size, extent, and curvature degree of roots and canals; the root canal shape, whether it is round, oval, or has any other form at any level of the root; and the status of the surrounding bone (Bóveda & Kishen, 2015). Then, based on the knowledge of root and canal morphologies, access cavity design can be mentally delineated according to a specific emergence profile of each canal orifice onto the occlusal surface. The convergence degree of the emergence profiles ultimately

determines the size/shape of access preparation, an approach known as image-guided access (Khademi, 2017). As previously discussed in this review, the combined use of CBCT and intra-oral optical scanning of the region of interest, the guided-access cavity, can potentiate the accuracy of guided drilling of teeth with anatomical anomalies or pulp calcification (Moreno-Rabié et al., 2020).

Visual magnification and illumination

One of the major limitations imposed by minimally invasive access cavities is to adequately map the pulp chamber floor in order to identify the root canal orifices.



FIGURE 15 (a) Tomographic images of a symptomatic maxillary central left incisor with chronic apical periodontitis and pulp canal obliteration showing the access planning with the Navident system; (b–e) Preoperative tomographic and radiographic images showing a patent apical canal, the obliteration of the coronal and middle canal thirds, and an apical lesion located at the mesial aspect of the root associated with a large lateral canal; (f) The use of the dynamic Navident system allowed to locate, prepare, and (g) fill the root canal through a conservative access cavity (Courtesy of Dr. Felipe Restrepo)

The rationale of preserving as much as possible of the pulp chamber roof implies a natural reduction in light propagation to the pulp chamber. With reduced light, visual acuity is severely compromised, especially if no

magnification is used. In that sense, magnification and illumination tools, such as loupes, and, especially, the operating microscope, play an essential role to provide the operator with adequate vision of the reduced

FIGURE 16 (a) Preoperative radiographic image of a symptomatic maxillary central right incisor with pulp canal obliteration; (b) Access planning with the Navident system using tomographic images; (c) Palatal view of the tooth showing the conservative access preparation and a size 06 K-file inserted at the working length after the root canal path located with the Navident system; (d) Immediate postoperative radiographic image of the tooth after filling procedures (Courtesy of Dr. Paula Villa)

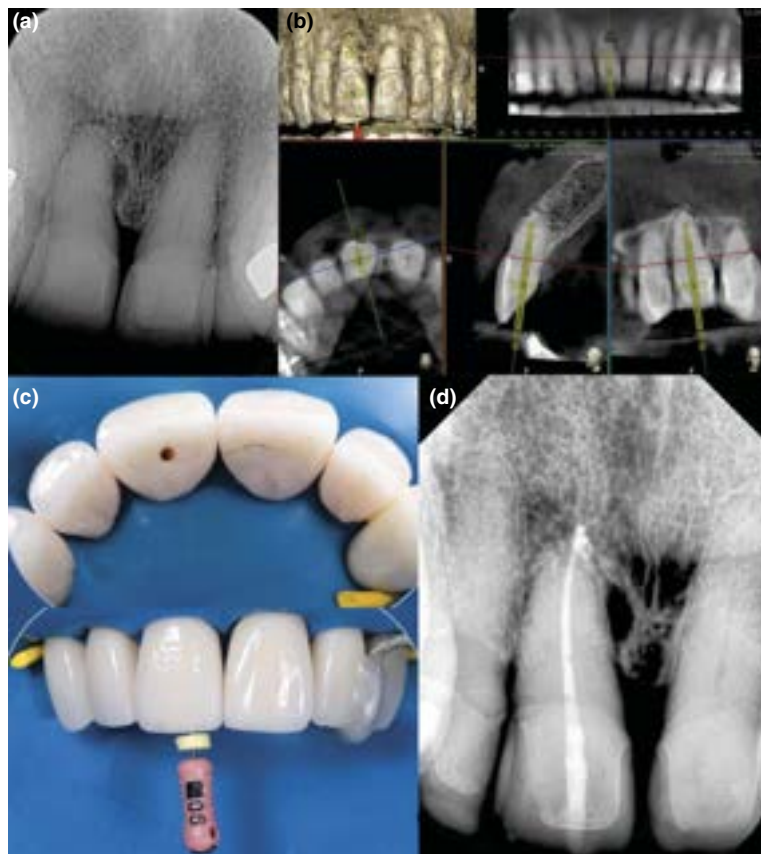
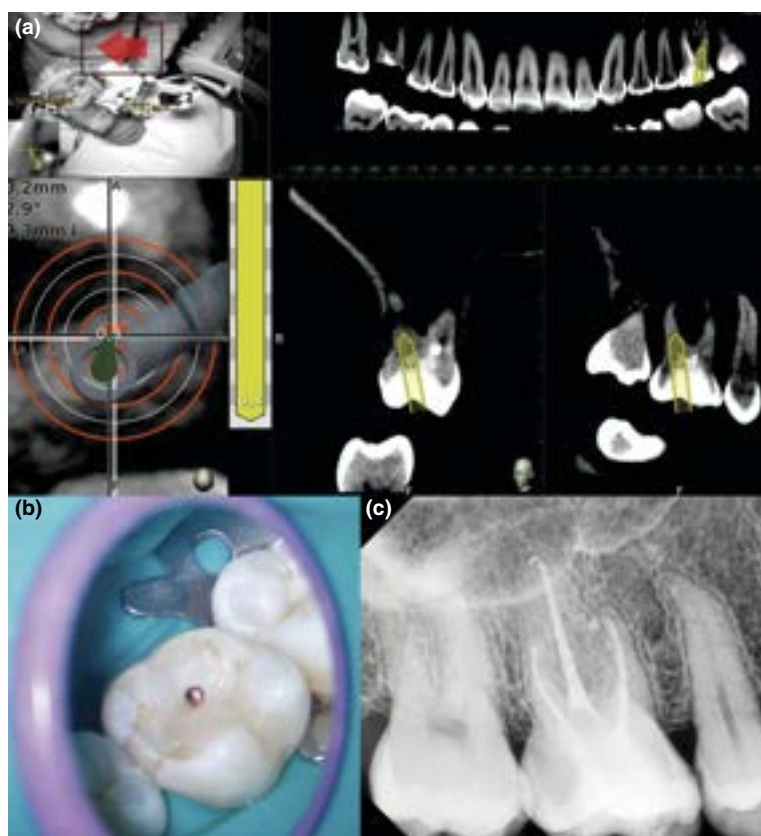


FIGURE 17 Selective retreatment procedure in a maxillary right first molar with pulp obliteration of the distobuccal canal. (a) Real-time tracking image with the Navident system while accessing the distobuccal canal; (b) Occlusal view of the tooth demonstrating the conservative cavity prepared to locate, prepare, and fill the distobuccal canal; (c) Immediate postoperative radiographic image of the tooth after filling the distobuccal root canal (Courtesy of Dr. Paula Villa)



operative field. In fact, a high frequency of canal orifice location using microscope-aided vision was already reported (Khalighinejad et al., 2017), even though no

robust clinical trial has been published to certify the role of magnification in the outcome of root canal treatment (Del Fabbro et al., 2009). In spite of lack of evidence,

TABLE 3 Advantages and drawbacks of the Dynamic Navigation Systems (DNS) in endodontics

Advantages	Drawbacks
• The CBCT and intraoral scan acquisitions, planning, and treatment can be performed on the same day reducing chairside time and radiation exposure (Dianat et al., 2020, 2021; Torres et al., 2021a). • Water-cooling is improved as there is no barrier between the water source and the bur reducing the risk of tooth structure damage due to overheating (Chong et al., 2019; Torres et al., 2021a). • It can be used in cases of limited vertical space as a guide is not necessary (Dianat et al., 2020, 2021; Torres et al., 2021a). • Any bur can be used as there is no special coupling system (Torres et al., 2021a). • Guidance failures due to poorly fitting guides do not occur (Stefanelli et al., 2019). • The planning is simplified as there is no need for a guide design (Dianat et al., 2020, 2021; Torres et al., 2021a). • Multiple paths for the bur in multi-canal teeth can be planned and executed easily compared to the SG technique (Torres et al., 2021a). • DNS increases intraoperative safety and is superior in accuracy to freehand treatment (Chong et al., 2019; Connert et al., 2021; Dianat et al., 2020; Jain et al., 2020b), minimizing the risk of iatrogenic damage, such as root perforation (Casap et al. 2004; Chong et al., 2019; Ewers et al. 2019). • Because there is no guide being placed on top of teeth, there is more vertical space and the view of the operation field is improved (Torres et al., 2021a). • DNS allows for live feedback during treatment, so corrections on the position of the bur can be made in real-time (Block & Emery, 2016; Block et al., 2017; Dianat et al., 2020; Jain et al., 2020a; Stefanelli et al., 2019).	• A high initial investment in equipment is needed, as well, larger volume scans for proper X-clip positioning, which may present a substantial change to the existing clinical workflow (Dianat et al., 2020, 2021; Torres et al., 2021a). • It requires a previous calibration process prior to treatment (Torres et al., 2021a). • It demands rigorous training of the operator prior to treatment (Torres et al., 2021a). The operator needs to maintain the drilling entry point, angle, pathway, and depth while looking at a display screen. As the “target” is displayed on the laptop monitor, the operator is looking away from the patient instead of at the tooth or their hands. Thus, motor control, eye-hand coordination, manual dexterity, system knowledge, and continued practice are necessary to attain proficiency (Chong et al., 2019; Dianat et al., 2020, 2021). • Tooth mobility may be a clinical condition that causes inaccuracy (Dianat et al., 2020). • The setup procedure is time-consuming, requiring the placement of the external monitors on a clear line of sight, which must be carefully thought through (Stefanelli et al., 2019). • Given their position and the need to angle the handpiece in molar teeth, the guidance system struggled to recognize the attached drill tag when it was out of the optical tracking field (Chong et al., 2019). • Patient movement during CBCT acquisition and radiopaque coronal restorations affects image quality, impedes virtual planning, and compromises the procedural accuracy (Dianat et al., 2020). • Current deviation values seem slightly high compared to static guides (Torres et al., 2021a). • The presence of a bulky handpiece tracker attachment makes it uncomfortable for routine use (Dianat et al., 2021).

the adoption of the operating microscope increases exponentially year-after-year (Brown et al., 2020; Kersten et al., 2008; Savani et al., 2014) and becomes mandatory when preparing minimally invasive access cavities (Bóveda & Kishen, 2015). Nevertheless, the natural difficulties in the learning curve of using microscopes in such reduced access cavities should not be undermined, and its educational consequences will be discussed later in this review.

Ultrasonic tips

As previously commented, clinical procedures can be performed with greater precision by using magnification and improved illumination. This approach, however, demands direct visual control which makes the use of high-speed burs impractical since the handpiece head usually prevents the visualization of the operative field during the procedures. In this scenario, the use of ultrasonic tips with

longer necks has emerged as one of the basic technical requirements for performing minimally invasive access cavities. Compared to conventional burs, the use of ultrasonic tips under magnification increases safety, cutting efficiency, and allows selective dentine removal (Plotino et al., 2007). In the first steps of access preparation, these tips can refine the prepared cavity and help remove pulp stones and locate canal orifices. Moreover, special ultrasonic tips may be used to mechanically clean the pulp chamber from remaining tissues and debris under the soffit, activate the irrigant solutions, and enhance disinfection (van der Sluis et al., 2007; Virdee et al., 2018).

High-flexible NiTi instruments

The use of the NiTi alloy to produce instruments for the mechanical preparation of root canals has raised the bar of endodontic practice to a new standard. Technological advancements with proprietary metallurgical treatment

of the NiTi alloy enabled the development of instruments containing substantial amounts of a stable martensite phase (Thompson, 2000), a condition that enhances flexibility and fatigue resistance (De-Deus et al., 2017; Silva et al., 2018, 2019a). Because of these improved properties, heat-treated high-flexible NiTi instruments can be successfully used not only for the management of root canals with severe curvatures (Bürklein et al., 2012; Filizola de Oliveira et al., 2019) but also to facilitate their insertion in teeth prepared with minimal access cavities since they can be effectively prebent. However, excessive angulation resulted from coronal interferences caused by the access design can increase the stress over the active part of the instrument (Pedullà et al., 2018, 2020), reducing its cyclic fatigue resistance (Silva et al., 2021a; Spicciarelli et al., 2020) and potentially increasing the risk of fracture (Lima et al., 2021).

Enhanced irrigation

Optimized irrigation protocols have been suggested for use with minimal access cavities because the preservation of the pulp chamber roof reduces the available space for the influx of the irrigant solution which may impair the intracanal disinfection process. These enhanced protocols include the use of ultrasonic devices (Silva et al., 2019b; van der Sluis et al., 2007), high-power sonic irrigation, multisonic ultracleaning system, and laser-assisted activation (Haapasalo et al., 2014; Peters et al., 2011; Sigurdsson et al., 2018). Although different irrigation resources are available nowadays, there remains a lack of studies testing the efficacy of such protocols in teeth with minimally invasive access cavities.

INFLUENCE OF MINIMALLY INVASIVE ACCESS CAVITY ON ENDODONTIC PROCEDURES: LABORATORY EVIDENCE

The overall description of the studies that evaluated the influence of access cavity design on endodontic procedures is summarized in Table 4. Their main topics include orifice location, mechanical preparation, canal cleaning, canal disinfection, instrument fracture, canal filling, retreatment, and restoration.

Orifice location

Missed canals are often responsible for the persistence of apical periodontitis (Baruwa et al., 2020; Costa et al., 2019), and locating all canal orifices is the first step to avoid it.

However, orifice location may be impaired by the limited view in minimal access cavities, particularly in cases in which orifices are not obvious pre-operatively. In a recent study, extracted human molars were examined in two clinical phases: after ConsAC and after TradAC, to determine the number and shape of canal orifices (Blauhut & Sonntag, 2020). The results revealed that the ConsAC approach was more susceptible to misinterpretation of the number and shape of canal orifices than TradAC. However, in a study comparing TradAC to ConsAC, with or without magnification, no difference was observed in the detection rate of the second mesiobuccal canal (MB2) of maxillary molars when troughing with an ultrasonic tip associated with magnification (Rover et al., 2017). Likewise, TradAC and ConsAC performed by an experienced endodontist using an operative microscope and thin ultrasonic tips had no influence in the detection of middle mesial canals in mandibular molars (Mendes et al., 2020). Conversely, another study (Saygili et al., 2018) demonstrated a greater MB2 detection rate in teeth prepared with TradAC (60%) and ConsAC (53.3%) than UltraAC (31.6%). (Table 4). Notwithstanding, the operators were blinded to the presence of these extra canals in these studies; the detection of canal orifices was not influenced by TradAC or ConsAC when using magnification/illumination and thin ultrasonic tips. In contrast, the UltraAC has impaired the detection of extra canals; however, it must be taken into consideration that the concept of minimally invasive access preparation requires the integration of 3D imaging technology for diagnosis as well as specific armamentarium (Bóveda & Kishen, 2015). Therefore, further studies are needed to evaluate whether the previous knowledge of the operator regarding the presence of extra canals would affect or not their detection. Also, studies are still needed to evaluate the influence of operator experience on the detection of these extra canals.

Mechanical preparation

Root canal preparation is one of the most important steps of root canal treatment, but the mechanical effects of the instruments over the root canal walls may result in iatrogenic damages, such as transportation, zips/elbows, ledging, apical blockage, loss of working length, perforations, extrusion of debris, and instrument fracture (Hülsmann et al., 2005). Over the years, numerous clinical procedures have been suggested to avoid these mishaps, including the enhanced visualization of the root canal space by performing proper cavity access (Gluskin et al., 2014). Notwithstanding the major technological advancements in the endodontic field in the last decades, canal preparation is still adversely influenced by the highly variable root and canal anatomy (Martins et al., 2021; Peters et al.,

TABLE 4 Overall description of the *ex vivo* and *in vitro* studies that evaluated different types of minimally access cavity preparations converting most of abbreviation types used in the original studies into the new proposal classification system to allow proper comparisons

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Abou-Elnaga et al.	2019	Egypt	Mandibular 1st molars	66	Control TradAC TrussAC	Fracture resistance	Control = TrussAC > TradAC	TrussAC improved the fracture resistance of endodontically-treated molars with mesio-occluso-distal cavities.
Alovisi et al.	2018	Italy/France	Mandibular molars	30	TradAC ConsAC	Micro-CT	TradAC > ConsAC	TradAC showed better preservation of the canal anatomy and less apical transportation than ConsAC.
Augusto et al.	2020	Brazil	Mandibular molars	32	TradAC UltraAC	Micro-CT Fracture resistance	(1) Untouched areas: TradAC = UltraAC; (2) Dentine removal: TradAC = UltraAC; (3) Transport: TradAC = UltraAC; (4) Fracture resistance: TradAC = UltraAC	No difference was observed between the access cavity designs regarding untouched areas, dentine removal, centering ability, and fracture resistance.
Barbosa et al.	2020	Brazil	Mandibular molars	30	TradAC ConsAC TrussAC	Culture Micro-CT Fracture resistance	(1) Bacterial reduction: TradAC = ConsAC = TrussAC; (2) Untouched areas: ConsAC > TradAC/ TrussAC = ConsAC/ TrussAC = TradAC; (3) Dentine removal: TradAC = ConsAC = TrussAC; (4) Transport: TradAC = ConsAC = TrussAC; (5) Voids in root fillings: TradAC = ConsAC = TrussAC; (6) Filling remnants in the pulp chamber: ConsAC = TrussAC > TradAC; (7) Fracture resistance: TradAC = ConsAC = TrussAC	There was no difference among the access cavity designs regarding bacterial reduction after preparation, dentine removal, centering ability, voids in root fillings and fracture resistance. Teeth with ConsAC and TrussAC presented more filling remnants in the pulp chamber than TradAC. The ConsAC group presented more unprepared areas than TradAC, but no differences were found between ConsAC and TrussAC groups, nor between TradAC and TrussAC.
Blauhut & Sonntag	2020	Germany	Molars	84	TradAC ConsAC	Visual evaluation of root canals under operating microscope	(1) Number of root canals detected: TradAC > ConsAC (2) Evaluation of the root canal geometry (round or oval): TradAC ≠ ConsAC	More root canals were detected in teeth with TradAC than in ConsAC. The evaluation of the root canal geometry changed between the two groups; more oval canals were detected in teeth with TradAC.
Chlup et al.	2017	Czech Republic	Premolars	60	Control TradAC ConsAC	Fracture resistance	Control = TradAC = ConsAC	There was no difference in the fracture resistance between TradAC and ConsAC compared to the control group.
Corsentino et al.	2018	Italy	Mandibular molars	100	Control TradAC ConsAC TrussAC	Fracture resistance	Control > TradAC = ConsAC = TrussAC	TrussAC did not improve the fracture resistance of teeth. The loss of mesial and distal ridges significantly decreased the strength resistance, independent of the access cavity type.

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Eaton et al.	2015	USA	Mandibular molars	30	ConsAC SLF SLR	Micro-CT	ConsAC > SLF > SLR	ConsAC showed the highest mean primary angle at the maximum curvature of mesial root canals.
Elkholly et al.	2021	Egypt/Australia/ Korea	Mandibular 1st molars	4	Control TradAC ConsAC TrussAC	FEA	Life span: TradAC < ConsAC = TrussAC	The TradAC models showed lower life span than ConsAC and TrussAC.
Freitas et al.	2020a	Brazil	Maxillary molars	20	TradAC ConsAC	Micro-CT	(1) Dentine removal: TradAC = ConsAC (2) Transport: TradAC = ConsAC	The type of endodontic access cavity did not influence root canal preparation.
Guler	2020	Turkey	Maxillary molars	8	TradAC UltraAC	FEA	Stress values: UltraAC > TradAC	Stress values for TradAC were smaller than those for UltraAC.
Isufi et al.	2020	Italy	Premolars and molars	120	TradAC ConsAC UltraAC	CBCT	Volume of dentin and enamel removed: UltraAC < ConsAC < TradAC	The percentage of volume of dentin and enamel removed was significantly higher as the access cavity was less conservative.
Ivanoff et al.	2017	USA	Mandibular premolars	45	Control TradAC ConsAC	Fracture resistance	Control = TradAC = ConsAC	ConsAC did not improve the fracture resistance of teeth with mesio-occlusal restored cavities compared to TradAC.
Jiang et al.	2018	China	Maxillary 1st molars	3	TradAC ConsAC ExtAC	FEM	(1) Occlusal stress: TradAC = ConsAC = ExtAC (2) Pericervical dentine stress: ConsAC < TradAC < ExtAC	The stress on the pericervical dentine increased with the enlargement of the access cavity.
Karobari et al.	2021	Malaysia	Mandibular 1st molars	80	Control TradAC ConsAC TrussAC	Fracture resistance	Control > TrussAC; Control > ConsAC; Control > TradAC; ConsAC > TradAC; TrussAC > TradAC; ConsAC = TrussAC	Teeth with TradAC presented lower fracture resistance than control teeth and teeth with ConsAC and TrussAC. However, the fracture resistance of teeth with ConsAC and TrussAC did not differ from each other. The experimental groups presented higher number of unrestorable fractures compared to the control group.
Krishnan et al.	2014	Canada	Maxillary central incisors, mandibular 2nd premolars and mandibular 1st molars	90	Control TradAC ConsAC	Micro-CT Fracture resistance	(1) Untouched canal walls: distal canal (ConsAC > TradAC); mesial canal, incisor and premolar canals (ConsAC = TradAC); (2) Dentine removal: incisors (TradAC > ConsAC); premolars (TradAC > ConsAC); molars (TradAC > ConsAC); (3) Fracture resistance: incisors (Control = TradAC = ConsAC); premolars (Control = ConsAC > TradAC); molars (Control = ConsAC > TradAC)	ConsAC resulted in significantly less dentin removal, improved fracture resistance (mandibular premolars and molars), and high untouched dentine walls after preparation at the apical third of distal root canals, compared to TradAC.

(Continues)

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Lima et al.	2021	Brazil	Mandibular molars	40	TradAC UltraAC	Micro-CT Fracture resistance	(1) Untouched areas: UltraAC > TradAC; (2) Dentine removal; UltraAC/XP < TradAC/XP = UltraAC/RC = TradAC/RC; (3) Hard tissue debris accumulation: TradAC/XP = UltraAC/XP < UltraAC/RC = TradAC/RC (4) Transport: MB canals: TradAC/XP < UltraAC/XP = UltraAC/RC = TradAC/RC; ML and D canals: TradAC/XP = UltraAC/XP < UltraAC/RC = TradAC/RC; (5) Voids in root fillings: UltraAC > TradAC; (6) Filling remnants in the pulp chamber: UltraAC > TradAC; (7) Fracture resistance: UltraAC = TradAC	Teeth with UltraAC presented more untouched areas, voids in root fillings and filling remnants in the pulp chamber compared to TradAC, regardless of the instrument used. UltraAC/XP showed less root dentine removal, and more hard tissue debris accumulation whilst TradAC/XP had less canal transportation, than the other groups. There was no difference between the access cavity designs regarding fracture resistance.
Lin et al.	2020	Taiwan	Maxillary and mandibular molars	36	TradAC ConsAC UltraAC	CBCT	Cervical dentine removal: TradAC > ConsAC = UltraAC	Cervical dentine removal was higher with TradAC.
Makati et al.	2018	India	Molars	60	TradAC ConsAC	CBCT/Fracture resistance	(1) Dentine thickness: ConsAC > TradAC (2) Fracture resistance: ConsAC > TradAC	ConsAC doubled the fracture resistance of teeth compared to TradAC.
Marinescu et al.	2020	Romania	Molars	20	Control TradAC ConsAC UltraAC	Fracture resistance	Control = ConsAC > UltraAC > TradAC*	Increased fracture resistance in teeth was observed with ConsAC and UltraAC, compared to TradAC.
Maske et al.	2021	Brazil	Mandibular molars	50	Control TradAC ConsAC	Fracture resistance	Control > ConsAC = TradAC	There was no difference in the fracture resistance between TradAC and ConsAC.
Mendes et al.	2020	Brazil	Mandibular 1st molars	60	TradAC ConsAC	Detection of middle mesial canals: TradAC = ConsAC		The detection of middle mesial canals in mandibular molars was not affected by the access cavity design.
Moore et al.	2016	Canada	Maxillary molars	57	Control TradAC ConsAC	Micro-CT Fracture resistance	(1) Modified canal walls: ConsAC = TradAC (2) Axial microstrain: ConsAC = TradAC (3) Fracture resistance: Control > TradAC = ConsAC	ConsAC performed similarly to TradAC regarding the mean proportion of modified canal walls, axial microstrain values, and fracture resistance.
Mustafa et al.	2020	Saudi Arabia	Mandibular molars	42	Control TradAC ConsAC	Fracture resistance	(1) Teeth with three residual walls: ConsAC = TradAC (2) Teeth with two residual walls: ConsAC > TradAC	There was no difference in the fracture resistance between ConsAC and TradAC in teeth with three residual coronal walls, but with two residual walls teeth with ConsAC presented higher resistance.
Neelakantan et al.	2018	China	Mandibular 1st molars	32	TradAC TrussAC	Histology	Remaining pulp tissue in the pulp chamber (TrussAC > TradAC) and mesial canal system (TrussAC = TradAC)	TrussAC showed higher amount of remaining pulp tissue in the pulp chamber than TradAC, but no difference within the mesial root canal system.

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Niemi et al.	2016	USA	Mandibular premolars	48	TradAC ConsAC	Root sectioning	Filling remnants after retreatment: ConsAC > TradAC	ConsAC resulted in more filling remnants than TradAC. Neither ProFile Vortex Blue nor TRUShape was able to remove all filling materials. ProFile Vortex Blue removed less filling material with the ConsAC mostly at the coronal and middle thirds. More time was required for retreatment of teeth with ConsAC using the TRUShape system.
Pereira et al.	2021	Brazil	Maxillary premolars	90	Control TradAC ConsAC	Micro-CT Fracture resistance FEA	(1) Untouched areas: ConsAC > TradAC; (2) Transport: ConsAC > TradAC; (3) Voids in restoration: ConsAC > TradAC; (4) Filling remnants in the pulp chamber: ConsAC > TradAC; (5) Fracture resistance: Control = ConsAC = TradAC; (6) Stress concentration areas: Control = ConsAC = TradAC	Teeth with ConsAC presented more canal transportation, untouched areas, voids in restoration, and filling remnants in the pulp chamber than TradAC. There was no difference between the access cavity designs regarding fracture resistance. In restored teeth, the stress distribution pattern was similar among the different access cavities.
Plotino et al.	2017	Italy	Premolars and molars	160	Control TradAC ConsAC UltraAC	CBCT Fracture resistance	Control = ConsAC = UltraAC > TradAC	TradAC showed higher fracture resistance than ConsAC and UltraAC in non-carious teeth. Unrestorable fractures were more frequent in the experimental groups than in the control group.
Özyürek et al.	2018	Turkey	Mandibular molars	100	Control TradAC ConsAC	Fracture resistance	Control > TradAC = ConsAC	ConsAC did not improve the fracture resistance of teeth with class II cavities compared to TradAC. More restorable fracture patterns were observed in teeth with ConsAC.
Reddy et al.	2020	India	Mandibular 3rd molar	70	Control TradAC ConsAC UltraAC	CBCT Fracture resistance	(1) Root canal filling efficacy: Control = TradAC = ConsAC = UltraAC (2) Fracture resistance: Control = UltraAC > ConsAC = TradAC	There was no difference among the groups regarding the efficacy and voids on root canal filling. The fracture resistance of control teeth and teeth with UltraAC was higher than with ConsAC and TradAC.

(Continues)

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Roperto et al.	2019	USA/Brazil	Maxillary 1st premolars	32	Control TradAC ConsAC ConsAC.DW	Fracture resistance FEA	Control = TradAC = ConsAC = ConsAC.DW	ConsAC performed similarly to the TradAC and intact teeth in terms of fracture resistance strength. Stress level on the palatal cusps and proximal crests was slightly increased in the TradAC. In the restored teeth, the stress levels of the experimental groups were similar to those of the control group.
Rover et al.	2017	Brazil	Maxillary molars	30	TradAC ConsAC	Micro-CT Fracture resistance	(1) Non-prepared area: TradAC = ConsAC (2) Hard tissue debris accumulation: TradAC = ConsAC (3) Transport: ConsAC > TradAC (4) Fracture resistance: TradAC = ConsAC	ConsAC and TradAC performed similar in terms of nonprepared areas, debris accumulation, and fracture resistance. Transportation was higher at the palatal canal of ConsAC teeth. In the distobuccal canals, ConsAC maintained the preparation more centralized 5 mm from the apex. A higher detection of MB2 canal with or without magnification was observed in the TradAC teeth, but no difference was observed when ultrasonic tips were associated to magnification.
Rover et al.	2020	Brazil	Mandibular incisors	40	TradAC ConsAC	Micro-CT Fracture resistance	(1) Untouched areas: TradAC = ConsAC; (2) Dentine removal: TradAC = ConsAC (3) Hard tissue debris accumulation: TradAC = ConsAC (4) Transport: TradAC = ConsAC (5) Voids in root fillings: ConsAC > TradAC; (6) Filling remnants in the pulp chamber: TradAC = ConsAC; (7) Fracture resistance: TradAC = ConsAC	There was no difference between the access cavity designs regarding untouched areas, dentine removal, centering ability, accumulation of hard tissue debris, and filling remnants in the pulp chamber and fracture resistance. Teeth with ConsAC presented more voids in root fillings than TradAC.
Saber et al.	2020	Egypt	Mandibular 1st molars	4	Control TradAC ConsAC TrussAC	FEA	Stress concentration in cervical region: TrussAC > ConsAC > TradAC.	Decreasing the size of the access cavity was associated with higher cervical stresses. Increasing the size of the access cavity was associated with the transmission of stresses to a further apical direction, regardless of the extent of root canal enlargement.
Saber et al.	2020	Iran	Mandibular molars	60	Control TradAC TrussAC	Fracture resistance	(1) Without termocycling: Control = TrussAC > TradAC (2) With termocycling: Control > TrussAC > TradAC	Under thermal stress, TrussAC increased the fracture strength of teeth compared with the TradAC.

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Sabeti et al.	2018	USA	Maxillary molars	48	Control TradAC ConsAC	Fracture resistance	Control > TradAC = ConsAC	ConsAC did not improve the fracture resistance of maxillary molars compared to TradAC.
Santosh et al.	2021	India	Mandibular molars	40	Control TradAC ConsAC TrussAC	Fracture resistance	Control > TrussAC; Control > ConsAC; Control > TradAC; ConsAC > TradAC; TrussAC > TradAC; ConsAC = TrussAC	Teeth with TradAC presented lower fracture resistance and more unresorable fractures than all other groups. The fracture resistance of teeth with ConsAC and TrussAC did not differ from each other.
Saygili et al.	2018	Turkey	Maxillary 1st molars	60	TradAC ConsAC UltraAC	CBCT	MB2 orifice location: TradAC = ConsAC > UltraAC	Detection of MB2 orifice was lower in UltraAC teeth compared to TradAC and ConsAC.
Silva et al.	2020a	Brazil	Maxillary premolars	20	TradAC UltraAC	Micro-CT Fracture resistance	(1) Untouched areas: TradAC = UltraAC; (2) Hard tissue debris accumulation: UltraAC > TradAC; (3) Voids in root fillings: TradAC = UltraAC; (4) Filling remnants in the pulp chamber: UltraAC > TradAC; (5) Preparation time: UltraAC > TradAC; (6) Fracture resistance: TradAC = UltraAC	UltraAC did not influence the quality of root canal filling or the fracture resistance of the teeth compared to TradAC, but resulted in more debris accumulation after preparation, more filling remnants at the pulp chamber after obturation, and increased time required to perform the endodontic treatment.
Silva et al.	2020b	Brazil	Maxillary premolars	20	TradAC UltraAC	Micro-CT	Voids in restoration: UltraAC > TradAC	It was observed more voids in resin composite restorations of maxillary premolars with UltraAC than TradAC.
Silva et al.	2021a	Brazil	Mandibular 1st molars	60	TradAC UltraAC	Micro-CT Fracture resistance	(1) Dentine removal: TradAC > UltraAC (2) Fracture resistance: TradAC = UltraAC	Despite the higher volume of dentine removal in teeth with TradAC than UltraAC, there was no difference in the fracture resistance between the access cavities.
Silva et al.	2021b	Brazil	Mandibular molars	40	TradAC UltraAC	Cyclic fatigue resistance	Cyclic fatigue resistance of reciprocating instruments: TradAC > UltraAC	The instruments used in UltraAC presented less cyclic fatigue resistance than the instruments used in TradAC.
Spicciarelli et al.	2020	Italy	Maxillary central incisors and maxillary 1st premolars	80	TradAC ConsAC	Fracture resistance/ Cyclic fatigue resistance	(1) Fracture resistance: TradAC = UltraAC (2) Cyclic fatigue resistance of reciprocating instruments: TradAC > UltraAC	There was no difference in the fracture resistance between TradAC and ConsAC. The instruments used in ConsAC presented less cyclic fatigue resistance than the instruments used in TradAC.

(Continues)

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Tüfenkçi & Yilmaz	2020	Turkey	Mandibular 1st molars	80	TradAC ConsAC	Culture	Bacterial reduction: TradAC = ConsAC	No difference was observed between the access cavity designs regarding the reduction of <i>E. faecalis</i> after canal preparation.
Tüfenkçi et al.	2020	Turkey	Mandibular 1st molars	80	TradAC ConsAC	Weighing apically extruded debris	Extruded hard tissue debris during instrumentation: ConsAC-RB > TradAC-OC = ConsAC-OC; TradAC-RB = ConsAC-OC = TradAC-OC	Reciproc Blue file used in teeth with ConsAC resulted in more debris extruded than the use of One Curve file in the same access cavity.
Vieira et al.	2020	Brazil/Norway	Mandibular incisors	62	TradAC ConsAC	qPCR Micro-CT	(1) Unprepared areas: ConsAC = TradAC (2) Number of positive samples for bacteria: ConsAC > TradAC	ConsAC performed similarly to TradAC in terms of unprepared canal areas but compromised the disinfection procedures. TradAC showed 82% lower bacteria counting than ConsAC.
Wang et al.	2020	China	Maxillary 1st molars	8	TradAC ConsAC	FEA	Stress concentration areas: TradAC > ConsAC	ConsAC reduced the failure probability and the maximum stress at the cervical region compared with TradAC.
Xia et al.	2020	China	Premolars	40	TradAC ConsAC	Micro-CT	(1) Untouched areas: ConsAC > TradAC; (2) Dentine removal: two roots: ConsAC < TradAC, single root: ConsAC = TradAC; (3) Increased canal volume and surface areas: TradAC = ConsAC; (4) Voids in root fillings: TradAC = ConsAC; (5) Fracture resistance: TradAC = ConsAC	Teeth with ConsAC presented more untouched areas than TradAC. Higher dentine removal in the biradicular premolars with TradAC compared to ConsAC, but this difference was not observed in single root premolars. There was no difference between the access cavity designs regarding increased canal volume and surface areas, voids in root fillings, and fracture resistance.
Yuan et al.	2016	China	Mandibular 1st molars	6	TradAC ConsAC	FEA	Stress concentration areas: TradAC > ConsAC	ConsAC reduced the stress distribution at the crown and the cervical level compared to TradAC. The highest stress concentration was observed at the margins of the cavities on the occlusal surface and was dependent on the enlargement of the canal orifices. ConsAC preserved almost 60% of hard dental tissue compared to TradAC.

TABLE 4 (Continued)

Authors	Year	Country	Teeth	n	Groups	Methods	Main results	Main findings
Zhang et al.	2019	China	Maxillary 1st molars	4	Control TradAC ConsAC UltraAC	Extended FEA	Stress concentration areas: ConsAC = TradAC > Control = UltraAC	Compared to TradAC, UltraAC increased the curvature of the endodontic instrument, and the estimated fracture load of dentine reduced the stress concentration. Peaks of maximum stress at the cervical region were higher as the removal of hard dental tissue increased. UltraAC and ConsAC preserved 43.5% and 34.3% of coronal hard tissue, respectively, compared to TradAC.

Abbreviations: CBCT, cone beam computed tomography; ConsAC, conservative access cavity; ConsAC.DW, ConsAC with divergent walls; Control, intact teeth; ExtAC, extended access cavity; FEA, Finite Element Analysis; MB2, second root canal of the mesiobuccal root of maxillary molars; Micro-CT, micro-computed tomography; OC, One Curve file; q-PCR, quantitative real-time polymerase chain reaction; RB, Recipro Blue file; RC, Recipro file; SLF, straight-line furection; SLR, straight-line radicular; TradAC, traditional access cavity; TrussAC, truss access cavity; UltraAC, ultra-conservative access cavity; XP, XP-endo instrument.

*The study do not present statistical analysis.

2001). Regardless of the instrument, micro-CT assessments revealed a large percentage of unprepared canal walls after shaping procedures (De-Deus et al., 2015a; Gagliardi et al., 2015; Martins et al., 2021; Versiani et al., 2013, 2018a, 2018b; Zuolo et al., 2018). In teeth with necrotic pulps, such areas might be covered with pulp tissue remnants, bacteria, and/or dentine chips (Siqueira et al., 2018) that may influence the long-term outcome of treatment (Chugal et al., 2017).

The present review found 20 studies on the influence of access cavity design on the percentage of unprepared canal walls (Augusto et al., 2020; Barbosa et al., 2020; Krishan et al., 2014; Lima et al., 2021; Pereira et al., 2021; Rover et al., 2017, 2020; Silva et al., 2020a; Vieira et al., 2020; Xia et al., 2020) and canal curvature/transportation (Alovisi et al., 2018; Augusto et al., 2020; Barbosa et al., 2020; Eaton et al., 2015; Freitas et al., 2021; Lima et al., 2021; Pereira et al., 2021; Rover et al., 2017, 2020; Zhang et al., 2019a) (Table 4). The first study that compared TradAC and ConsAC regarding root canal preparation using micro-CT was by Krishan et al. (2014). These authors reported that distal canals of mandibular first molars prepared with ConsAC had a greater percentage of untouched walls after preparation than teeth with TradAC, but sample selection was carried out using radiographic images which have critical methodological limitations. In other studies, the anatomical bias was reduced using micro-CT imaging to select samples from different groups of teeth, including maxillary molars (Rover et al., 2017), mandibular molars (Augusto et al., 2020; Barbosa et al., 2020; Lima et al., 2021), mandibular incisors (Rover et al., 2020; Vieira et al., 2020), and premolars (Pereira et al., 2021; Silva et al., 2020a; Xia et al., 2020). While no difference was observed between teeth with TradAC and ConsAC (Rover et al., 2017, 2020; Vieira et al., 2020), UltraAC (Augusto et al., 2020; Silva et al., 2020a), or TrussAC (Barbosa et al., 2020), other authors reported greater percentage of untouched canal walls after shaping in teeth prepared with ConsAC (Barbosa et al., 2020; Xia et al., 2020) and UltraAC (Lima et al., 2021; Pereira et al., 2021) than TradAC (Figure 18). These contradictory results suggest that further studies using pair-matched teeth selected by micro-CT (De-Deus et al., 2020) should be performed.

Canal transportation in teeth accessed with different cavity designs was evaluated using the palatal root of maxillary molars (Rover et al., 2017), the mesial root of mandibular molars (Alovisi et al., 2018; Augusto et al., 2020; Barbosa et al., 2020), the mesiobuccal root of mandibular molars (Freitas et al., 2021; Lima et al., 2021), maxillary premolars (Pereira et al., 2021), and mandibular incisors (Rover et al., 2020). In some studies, canal preparation in teeth with ConsAC (Alovisi et al., 2018; Rover et al., 2017) and UltraAC (Lima et al., 2021; Pereira et al., 2021) resulted in major

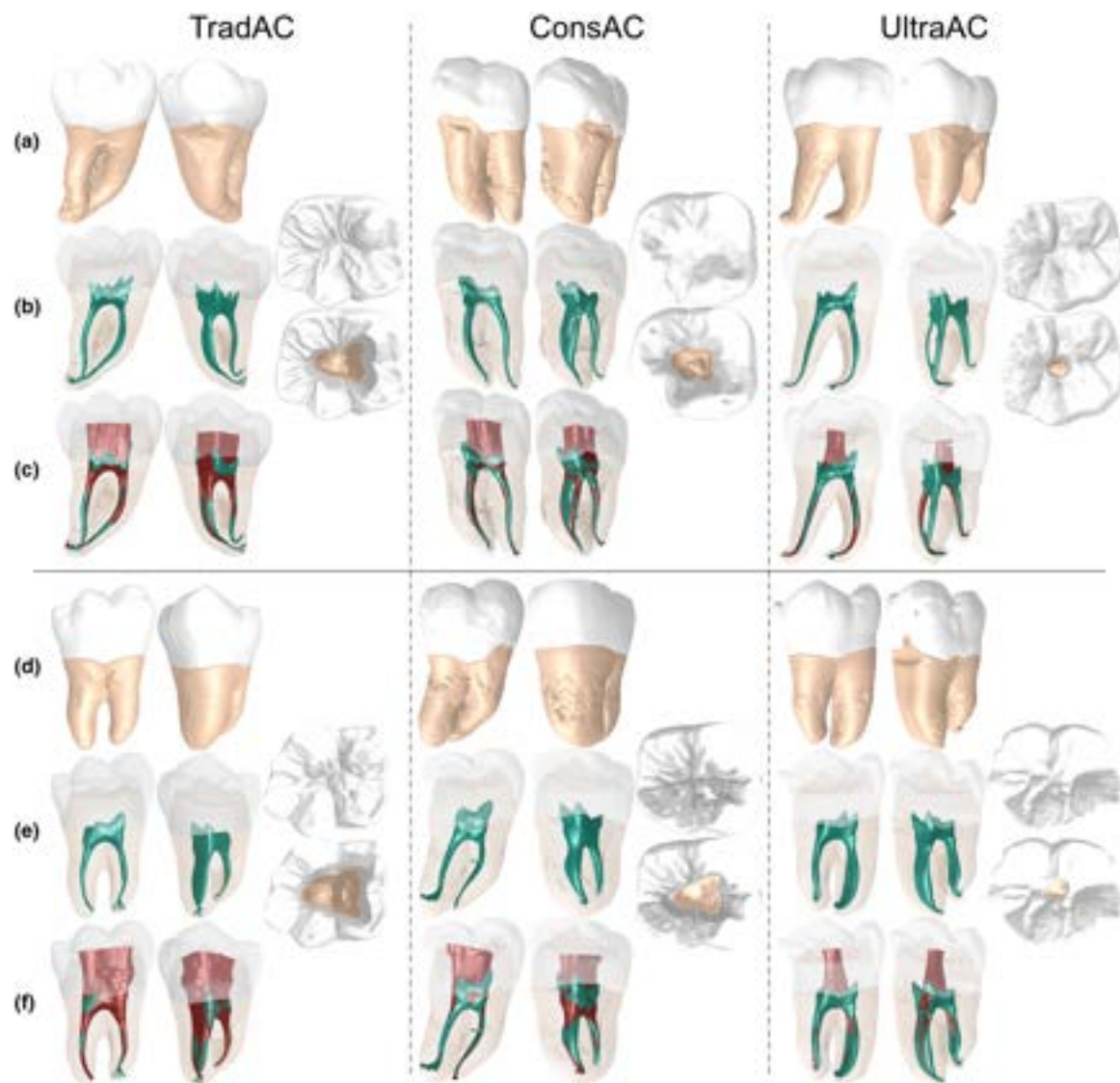


FIGURE 18 Schematic 3D renderings of TradAC, ConsAC, and UltraAC. In (a) and (d), the samples are seen in opaque images; in (b) and (e), the translucent samples show the pulp chamber and the root canals before (green) access and instrumentation; and in (c) and (f), the superposition of before (green) and after (red) access and instrumentation procedures, showing the non-prepared root canal areas. Occlusal views of teeth before and after the three different types of access (TradAC, ConsAC, and UltraAC) can also be visualized

deviation of the original anatomy, especially at the apical level. Eaton et al. (2015) and Zhang et al. (2019a) observed that the maximum angle of canal curvature was higher in teeth with ConsAC than TradAC. This would result in excessive pressure of the instrument against the outer aspect of the curve (Alovisi et al., 2018), increasing the risk of transportation during canal shaping, which may explain these results. Conversely, other studies reported no difference comparing teeth with TradAC to ConsAC (Barbosa et al., 2020; Freitas et al., 2021; Rover et al., 2020), UltraAC (Augusto et al., 2020), or TrussAC (Barbosa et al., 2020). In most of the studies, it was not possible to demonstrate the influence of mechanical preparation on canal transportation because only one NiTi system was used (Alovisi et al., 2018; Augusto et al., 2020; Barbosa et al., 2020; Freitas et al.,

2021; Rover et al., 2017, 2020). On the other hand, Lima et al. (2021) did not observe differences in the canal transportation of teeth with UltraAC prepared using Reciproc (VDW) or XP-Endo Shaper (FKG), while Pereira et al. (2021) demonstrated greater canal transportation when teeth with ConsAC were prepared with ProTaper Universal (Dentsply Maillefer) than Reciproc (VDW), Reciproc Blue (VDW), or HyFlex EDM (Coltene). It is important to observe that although micro-CT was used in some of these studies, the measurement of transportation included the linear analysis in just a few slices and only in one direction. Therefore, further studies with more relevant methodological design should be performed including the use of anatomically paired-teeth and evaluating the canal transportation along the entire z-axis of the root (Figure 19) in order to provide a

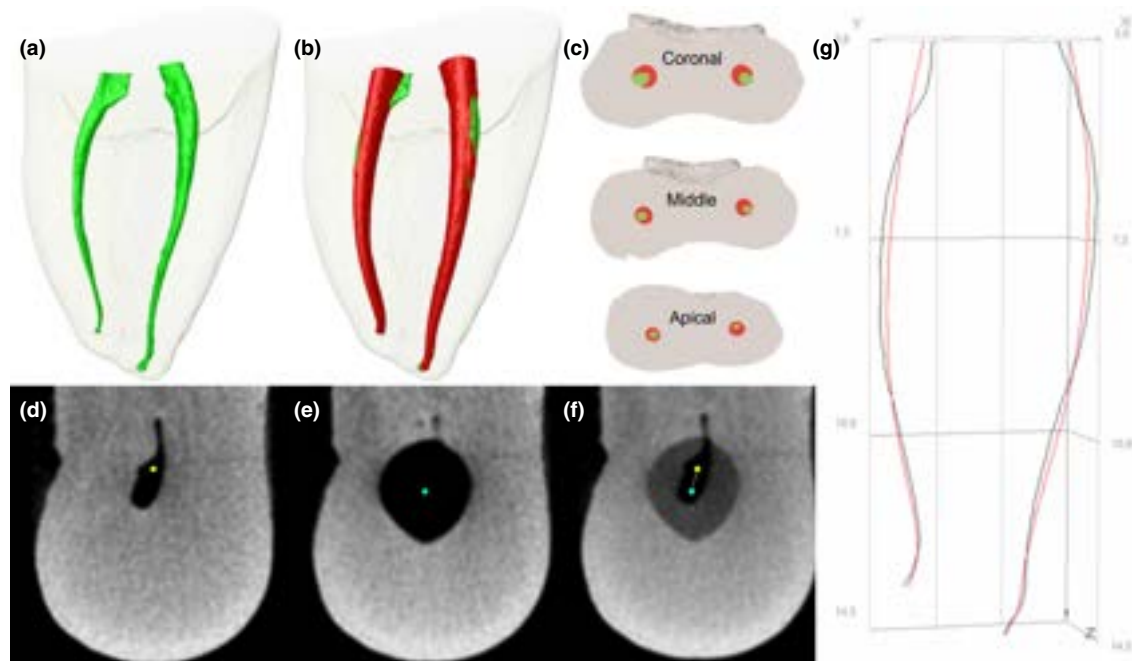


FIGURE 19 (a–b) Lateral views of 3D reconstructions of the internal anatomy of mesial roots of a mandibular molar before (green) and after (red) canal preparation with a rotary system. (c) Cross-sections of the superimposed root canals before (green) and after (red) preparation at the coronal, middle, and apical thirds. Canal transportation is assessed by using the centre of gravity before (d) (yellow circle) and after (e) (blue circle) in each slice. (f) Transportation (in mm) is calculated by comparing the centres of gravity before and after treatment in each slice (white line). Then, the centres of gravity are connected along the z-axis with a (g) fitted line through all cross-sections to obtain a 3D graph showing the pre-instrumentation (black line) and post-instrumentation (red line) root canal central axis

more reliable perspective of canal transportation throughout the entire canal system.

Instrument fracture

Two studies using mandibular molars (Silva et al., 2021a), maxillary central incisors, and maxillary first premolars (Spicciarelli et al., 2020) compared the influence of ConsAC (Spicciarelli et al., 2020) and UltraAC (Silva et al., 2021a) to TradAC regarding the cyclic fatigue resistance of reciprocating instruments. In both studies, instruments used in teeth prepared with minimally invasive access cavities were associated with less cyclic fatigue resistance values than in teeth with TradAC. This can be explained because in teeth with contracted cavities, the greater maximum angle of canal curvature increases the level of stress along the active part of the instrument (Pedullà et al., 2018, 2020), increasing the likelihood of fracture if it exceeds its endurance limit (Lopes et al., 2013; Özyürek et al., 2017) (Figure 20). Only two studies have examined instrument fracture in teeth prepared with ConsAC (2 Reciproc Blue R25; VDW) (Barbosa et al., 2020) and UltraAC (1 XP-Endo Shaper; FKG) (Lima et al., 2021). Although low fracture rates were found, the potential risk cannot be neglected considering that once fracture

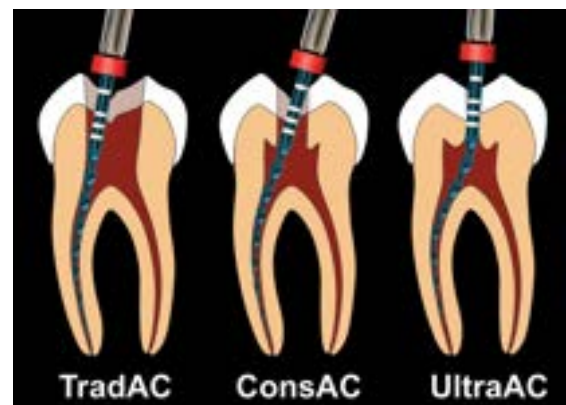


FIGURE 20 Schematic representation of NiTi instruments in TradAC, ConsAC, and UltraAC. It is possible to observe that a higher angle of curvature in the most coronal part of the instrument is present in the ConsAC and UltraAC, increasing the level of stress along the active part of the instrument and thus, the likelihood of fracture

occurs, attempts to remove the fragment is usually followed by unnecessary dentine removal, resulting not only in weakening the tooth structure but also violating the basic concept of minimally invasive preparation (Silva et al., 2020c). This is an important research topic, and more studies using pair-matched teeth are required.

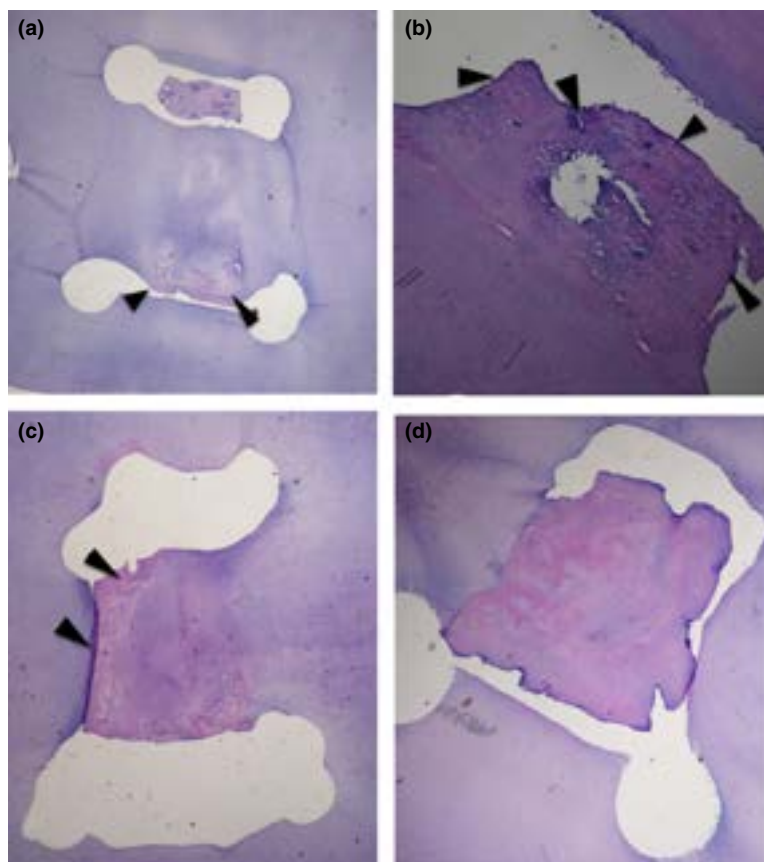


FIGURE 21 Neelakantan et al. (2018) study evaluated if TrussAC was able to debride the pulp chamber, root canals, and isthmus of mesial roots of mandibular molars in the same way as TradAC. The results demonstrated that remaining pulp tissue in the pulp chamber was significantly higher in TrussAC when compared to TradAC. However, no differences were observed in the root canals or the isthmus. Representative sections from the pulp chamber region of teeth prepared with (a and b) TradAC and (c and d) TrussAC. The black arrowheads indicate pulp tissue in the (a and c) pulp chamber floor, (c) the junction of the floor and walls, and the (a and b) junction of the floor and isthmus between root canals (Reprinted with permission)

Root canal cleaning

Comparison of minimally invasive and traditional access cavities regarding root canal cleaning was performed by evaluating pulp tissue remnants in the pulp chamber (Neelakantan et al., 2018) and debris accumulation produced by canal shaping as outcome variables of interest (Lima et al., 2021; Rover et al., 2017, 2020; Silva et al., 2020b; Tüfenkci et al., 2020) based on the rationale that they may interfere with the mechanical action of instruments and with flow dynamics of irrigants throughout the microenvironment of the canal system (De-Deus et al., 2015b; Siqueira & Roças, 2008).

According to Neelakantan et al. (2018), mandibular molars with TrussAC prepared using rotary instruments had greater amount of pulp tissue retained in the pulp chamber than TradAC probably because the remnants of the pulp chamber roof interfered with the flow of the irrigant solution delivered using conventional syringe irrigation (Figure 21). However, no supplementary irrigation or modified instruments were used in an attempt to remove the tissue remnants. UltraAC was also associated with greater amounts of accumulated debris in irregular areas of the canal system (Lima et al., 2021; Silva et al., 2020a) or even extruded through the apical foramen (Tüfenkci et al., 2020) than TradAC. On the other hand, TradAC and ConsAC performed similarly regarding debris

accumulation in maxillary molars (Rover et al., 2017) and mandibular incisors (Rover et al., 2020).

In general, the present findings suggest that TrussAC and UltraAC negatively affect intracanal cleaning conditions (Neelakantan et al., 2018) and debris accumulation produced during shaping procedures (Lima et al., 2021; Silva et al., 2020a; Tüfenkci et al., 2020). However, irrigation in these studies was performed using conventional syringe techniques with small-sized needles, while additional irrigant activating/agitation systems have been clearly recommended in teeth prepared with minimally invasive access cavities (Bóveda & Kishen, 2015). Therefore, additional studies are still necessary to provide better understanding of the impact of minimal access cavities on the effectiveness of cleaning and shaping procedures.

Root canal disinfection

Publications on root canal disinfection in teeth prepared with minimally invasive cavities are still scarce and controversial (Barbosa et al., 2020; Tüfenkci & Yilmaz, 2020; Vieira et al., 2020). Vieira et al. (2020) reported that the number of bacteria-positive samples collected from root canals of mandibular incisors with oval-shaped canals prepared with ConsAC was significantly greater (86%) than in teeth with TradAC (50%). However, even though

bacteria were detected by a very accurate method (quantitative polymerase chain reaction), bacterial sampling was performed using paper points, which is a technique well-known to overestimate the disinfection ability of chemomechanical procedures as it is not sensitive enough to detect the biofilm attached to the anatomical irregularities of the dentinal walls (Siqueira et al., 2013). Besides, irrigation was performed using the conventional syringe technique. In contrast, others reported no difference in bacterial reduction (*E. faecalis*) collected from mandibular molars prepared with ConsAC (Barbosa et al., 2020; Tüfenkci & Yilmaz, 2020) or TrussAC (Barbosa et al., 2020) compared to TradAC. These studies, however, used the oversimplistic colony-forming units, a limited method where clumps of bacterial cells can be miscounted as single colonies, and results are usually obtained after some days, making it unsuitable for serial longitudinal studies (Hazan et al., 2012).

Notwithstanding the results of Tüfenkci and Yilmaz (2020) that suggest that irrigant activation enhances the effectiveness of canal disinfection in teeth with minimal access cavities, it is also known that irrigation of minimal enlarged canals may have some geometrical disadvantages, such as limited penetration, needle wedging, vapour lock effect, and challenges associated with sonic/ultrasonic/apical negative pressure irrigation (Bóveda & Kishen, 2015). Therefore, since disinfection procedures can be impaired by contaminated pulp tissue remnants that may serve as a source for persistent infection and post-treatment disease, ultimately affecting the outcome of root canal treatment (Restrepo-Restrepo et al., 2019; Siqueira & Roças, 2008), further research is also required in this key area.

Root canal filling

The influence of minimal access cavities on the overall quality of the root canal filling was evaluated in eight studies (Barbosa et al., 2020; Lima et al., 2021; Niemi et al., 2016; Pereira et al., 2021; Reddy et al., 2020; Rover et al., 2017; Silva et al., 2021b; Xia et al., 2020) (Table 4). The first study compared the quality of canal filling in mandibular premolars with oval-shaped canals prepared with ConsAC or TradAC through radiographic analysis (Niemi et al., 2016). The authors concluded that warm lateral compaction was the best option for filling canals in teeth with minimally invasive access preparations because their small size hindered adaptation of the gutta-percha in the single-cone technique. Although some studies reported great percentage of voids in mandibular incisors (Rover et al., 2020) and molars (Lima et al., 2021) prepared with ConsAC and UltraAC, respectively, no differences were

reported in mandibular molars (ConsAC vs. TrussAC vs. TradAC) (Barbosa et al., 2020), mandibular third molars (ConsAC vs. UltraAC vs. TradAC) (Reddy et al., 2020), maxillary premolars (UltraAC vs. TradAC) (Silva et al., 2021b), and premolars (ConsAC vs. TradAC) (Xia et al., 2020).

An important aspect observed was the amount of remaining filling materials in the pulp chamber after filling. While Rover et al. (2020) reported no difference in mandibular incisors prepared with ConsAC and TradAC, other studies in posterior teeth (Barbosa et al., 2020; Lima et al., 2021; Pereira et al., 2021) reported larger amounts of remaining filling materials in the pulp chamber of teeth prepared with contracted cavities than that of TradAC, even using microscope magnification. In another study, the operator was unable to remove the remnants of filling materials from the pulp chamber prior to restoration of teeth prepared with UltraAC, even with the aid of ultrasonic tips, magnification under microscope, and extra time to complete the treatment (Silva et al., 2021b) (Figure 22). This extended operative period might contribute to the fatigue of both the patient and dentist, while the filling remnants can compromise aesthetics by causing tooth crown discoloration over time (Lenherr et al., 2012; Marchesan et al., 2018). Considering the controversial results published so far and the scarce number of studies, the influence of access cavity size on the quality of filling procedures remains a topic to be explored.

Retreatment

The influence of different access cavity designs on root canal retreatment was evaluated in only one study (Niemi et al., 2016), in which the effectiveness of TRUShape (Dentsply Sirona) and ProFile Vortex Blue (Dentsply Sirona) instruments for the removal of filling materials through TradAC and ConsAC in mandibular premolars was compared. As would be expected, more time was required to retreat the root canals of teeth with ConsAC, but the results suggested a possible interaction between the access cavity type and the instrument. While the combination of ConsAC with ProFile Vortex Blue rotary system was associated with greater amount of filling remnants, no difference was found in the retreatment of teeth with TradAC or ConsAC using TRUShape instruments. Yet, the evaluation of the percentage of remaining materials was achieved by sectioning the teeth and, consequently, there is no information regarding the quality of the root filling before the retreatment procedure. Moreover, single-rooted specimens certainly do not represent a typical anatomical endodontic challenge, which probably positively influenced the outcome of the study. Further studies

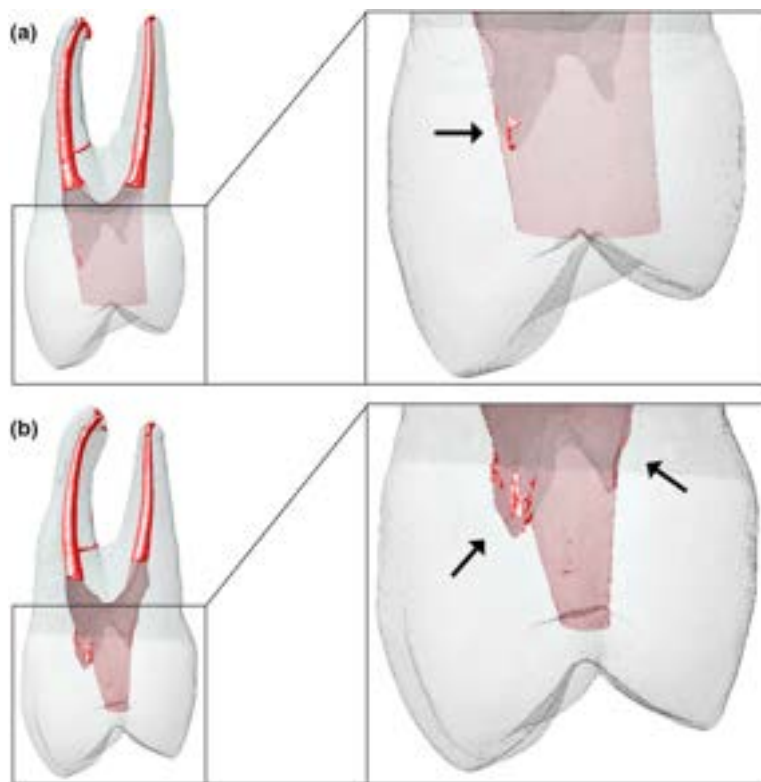


FIGURE 22 3D renderings from representative premolars showing (black arrows) the presence of remaining root fillings in the pulp chamber of (a) TradAC and (b) ConsAC after cleaning procedures. It is important to note the presence of root filling remnants at the pulp horns in ConsAC due to the difficulty to clean these areas

using non-destructive micro-CT imaging, in which the percentage of filling material remnants could be calculated on the basis of their total volume before retreatment, would provide more significant information regarding the efficiency of the retreatment procedures under different cavity designs.

Restoration

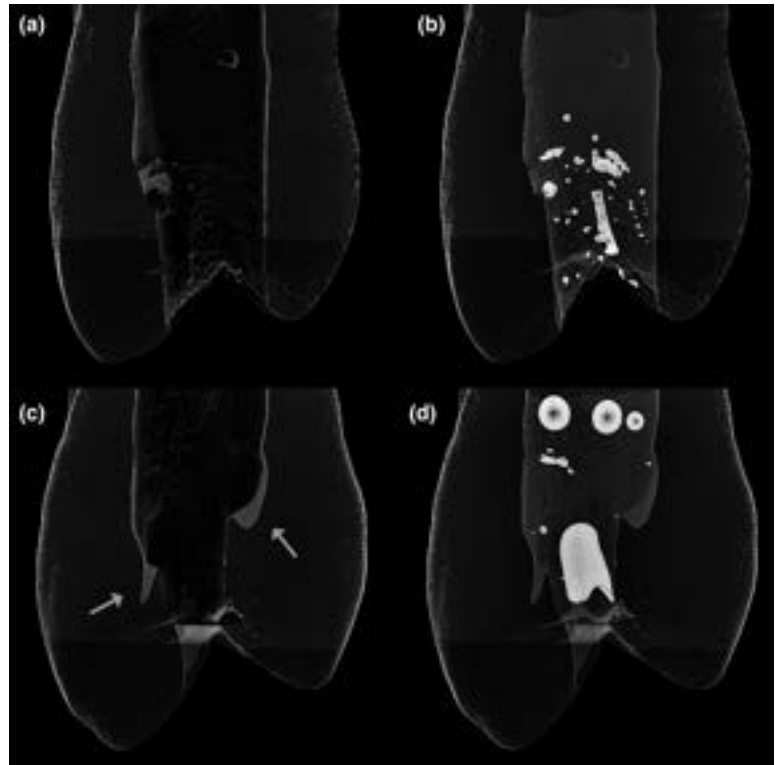
Only two studies have assessed the influence of different access cavity designs on restoration procedures and observed a higher percentage of voids within the composite restoration in premolars prepared with UltraAC (Silva et al., 2020b) and ConsAC (Pereira et al., 2021) than those prepared with TradAC. Silva et al. (2020b) used bulk fill flowable composite resin to fill the pulp chamber and incremental conventional composite resin as a capping layer to restore both access cavity groups, while Pereira et al. (2021) restored teeth in all test groups with different materials: conventional composite, regular bulk fill composite, or bulk fill flow combined with conventional composite. A qualitative analysis of the pulp chamber demonstrated that voids were mostly observed between the remnants of filling materials (located at the pulp horns and at buccal and lingual walls) and the layers of restorative materials (Figure 23).

CURRENT EVIDENCE OF MINIMAL CAVITIES ON THE FRACTURE RESISTANCE OF ROOT-FILLED TEETH

The aetiology of root fractures in filled teeth is complex and multifactorial and has been associated with a combination of anatomic and iatrogenic factors, including overpreparation of canals, post-space preparation and placement, number of canals, presence of isthmus, and root dimensions (Tamse, 2006; Versiani et al., 2015), most of them somehow related to the excessive removal of the dentine (Kishen, 2015; Tamse, 2006; Wang et al., 2020). The minimally invasive concept in endodontics was founded on the premise that dentine conservation during access cavity preparation is paramount to maintain optimal conditions for the long-term function and survival of root-filled teeth (Clark & Khademi, 2010a). It started as an empirical theory based on a series of cases (Clark & Khademi, 2010b) and evolved to a more structured concept requiring the use of 3D imaging technology, visual magnification, superior illumination, ultra-flexible instruments, and enhanced irrigation procedures (Bóveda & Kishen, 2015).

Although minimally invasive access is being embraced by some skilled clinicians, its influence on the fracture resistance of teeth still has limited evidence. Whilst eight

FIGURE 23 Representative 3D images showing (a) the resin restoration of the pulp chamber and (b) the voids inside the resin restoration in TradAC and (c) the gaps (white arrows) in resin restoration of the pulp chamber and (b) the increased volume of voids inside the resin restoration in ConsAC



studies reported greater fracture resistance of teeth with minimal access cavity preparations when compared to TradAC (Abou-Elnaga et al., 2019; Karobari et al., 2021; Krishan et al., 2014; Makati et al., 2018; Marinescu et al., 2020; Plotino et al., 2007; Saberi et al., 2020; Santosh et al., 2021), a total of 18 studies reported no difference among them (Augusto et al., 2020; Barbosa et al., 2020; Chlup et al., 2017; Corsentino et al., 2018; Ivanoff et al., 2017; Lima et al., 2021; Maske et al., 2021; Moore et al., 2016; Özyürek et al., 2017; Pereira et al., 2021; Roperto et al., 2019; Rover et al., 2017, 2020; Sabeti et al., 2018; Silva et al., 2020b, 2021b; Spicciarelli et al., 2020; Xia et al., 2020) (Table 5). It is likely that these conflicting outcomes can be partially explained by differences in the experimental methods. Yet, in several instances, the methodologies are so varied that a direct comparison amongst the results is unfeasible.

The morphology of the crown and the root has been considered important risk factors involved in tooth fracture (Kang et al., 2016; Qian et al., 2013). Consequently, it would be expected that a well-controlled laboratory study should take into consideration the external and internal morphologies of teeth as sampling criteria to increase the internal validity and reliability of the study. Nevertheless, whilst four studies did not report how sample selection was performed (Chlup et al., 2017; Makati et al., 2018; Mustafa et al., 2020; Reddy et al., 2020), most of them used the external measurement of teeth and/or conventional radiographic examination to select and allocate the specimens

into experimental groups (Corsentino et al., 2018; Ivanoff et al., 2017; Karobari et al., 2021; Krishan et al., 2014; Marinescu et al., 2020; Maske et al., 2021; Moore et al., 2016; Özyürek et al., 2017; Plotino et al., 2017; Roperto et al., 2019; Saberi et al., 2020; Sabeti et al., 2018; Santosh et al., 2021; Spicciarelli et al., 2020). Even though it is yet to be proven, this lack of anatomical matching raises questions regarding the trustworthiness of their results. It is possible that the volume of the pulp chamber as well as the thickness, height, and volume of the remaining dental hard tissues may directly affect the fracture resistance of teeth, parameters that can be exactly quantified by means of micro-CT technology in order to create a reliable baseline. Strict sample selection criteria based on the external and internal morphologies of teeth using micro-CT imaging was done in nine studies and, in all of them, no difference on the fracture resistance was found amongst teeth prepared with different types of access cavities (Augusto et al., 2020; Barbosa et al., 2020; Lima et al., 2021; Pereira et al., 2021; Rover et al., 2017, 2020; Silva et al., 2020a, 2021b; Xia et al., 2020).

After using a strict selection criterion, specimen preparation for the fracture test is also a critical step that may affect the experimental results. In some studies, different types of occlusal cavities were prepared prior to accessing the pulp chamber in an effort to simulate a common clinical scenario observed in teeth referred for endodontic treatment (Abou-Elnaga et al., 2019; Corsentino et al., 2018; Ivanoff et al., 2017; Mustafa et al., 2020; Özyürek

et al., 2017; Reddy et al., 2020) (Table 5). Mustafa et al. (2020) reported greater fracture resistance of teeth with ConsAC than TradAC only when teeth had two residual walls, while no difference was observed in the presence of three residual walls. It is important to emphasize that in this study, teeth were not adhesively restored prior to fracture testing. In another study using a similar approach (Reddy et al., 2020), teeth with UltraAC had greater fracture resistance than TradAC, but no difference was found between ConsAC and TradAC. Although this approach seems more likely in real-life cases, unfortunately, using real teeth, it is not possible to standardize the volume of dentine to be removed or the exact dimensions and shape of the cavity preparation. Besides, it is also known that a mesio-occlusal-distal cavity usually reduces tooth stiffness by more than 60% (Kishen, 2015; Reeh et al., 1989). Thus, these studies ended up introducing an uncontrolled confounding variable to the test.

Regarding sample preparation before the fracture resistance test, in some studies, root canals were not prepared (Mustafa et al., 2020; Sabeti et al., 2018) or filled (Ivanoff et al., 2017; Krishan et al., 2014; Moore et al., 2016; Mustafa et al., 2020; Sabeti et al., 2018), and the crowns were not restored (Krishan et al., 2014; Mustafa et al., 2020; Sabeti et al., 2018) (Table 5). Notwithstanding the authors' justification that these procedures avoided adding confounding factors to the variables, it was not taken into consideration that the dentine removed by mechanical preparation would also affect the fracture resistance of teeth (Tang et al., 2010), the canal filling might contribute to the re-establishment of the fracture resistance of teeth (Sandikci & Kaptan, 2014), and the restoration can recover the fracture resistance of root filled teeth by approximately 80% (Hamouda & Shehata, 2011). Consequently, the conclusions drawn from these studies must be taken with caution.

In studies using the non-destructive micro-CT analytical method, the same specimen serving as its own control and evaluation over time is possible. A control group is an essential part of a scientific investigation as it allows the reliability of the test to be confirmed, providing a reliable baseline to compare the results of the experimental groups (Versiani et al., 2015). Considering that fracture tests are destructive, sound teeth are usually used as controls. In a close-to-ideal experimental model, control samples should be pair-matched to the experimental groups in terms of aging, storage conditions, and external and internal dimensions. Even though most of the selected studies used sound teeth as controls, sample selection was not performed using strict methodological criteria (Table 5) and, therefore, these findings are also open to criticism.

A possible solution to overcome the aforementioned methodological drawbacks is to use an approach based

on a combination of virtual models and simulation, the so-called Finite Element Analysis. This method was used in eight studies to evaluate stress concentration areas on standardized 3D models obtained from real teeth in which different types of access cavities were simulated (Elkholy et al., 2021; Guler, 2020; Jiang et al., 2018; Pereira et al., 2021; Saber et al., 2020; Wang et al., 2020; Yuan et al., 2016; Zhang et al., 2019b). In most of these studies, larger stress concentration areas were found at the cervical region of teeth prepared with TradAC than ConsAC suggesting that the amount of dentine removed from the coronal part of teeth during access preparation procedures may affect their fracture resistance.

Based on these laboratory results, it may be inferred that there is no balance between the experimental and clinical outcomes: while available experimental methods are unsound, clinical evidence is still lacking. In fact, no model has been validated to actually rank the materials and techniques mostly because samples were not properly standardized and prepared. Therefore, considering these conflicting findings and systematic flaws, well-designed and better controlled *ex vivo* studies using innovative methodological approaches are required to clarify the role of access preparation on the overall fracture resistance strength of teeth.

METHODOLOGICAL CONSIDERATIONS

As the majority of accumulated knowledge on minimally invasive access preparation comes from laboratory research, its translation to the clinical setting must be considered with caution, especially since a close-to-ideal design has still to be defined. It should not be forgotten that a usual misunderstanding lies in the belief that the main purpose of an experimental model is to mimic, as best as possible, the clinical conditions. This is fundamentally mistaken as clinical conditions cannot be entirely reproduced by benchtop studies. Rather, any source of bias should be carefully considered and controlled to allow adequate conditions to isolate the variable of interest during the experiment which, in the present case, is the direct effect of minimal access cavities. When such conditions are created, laboratory results could be used to predict, at least to some degree, the clinical behaviour of the tested material/technique, and this should be taken as the paramount purpose of a laboratory assay (Van Meerbeek et al., 2010). However, in order to provide reliable data by avoiding bias, some basic methodological design requirements must be considered, including sample size, sample storage, methods for sample selection (criteria), the analytical method *per se*, data processing, and interpretation. Some of these factors are addressed in the next sections.

TABLE 5 Methodological details of studies reporting the influence of minimally invasive access cavity preparation on the fracture resistance of teeth

Reference	Tooth type	Main results	Sample age	Freshly extracted teeth	Occlusal cavity	Control group	Canal shaping	Canal obturation	Tooth restoration	Selection method
Abou-Elnaga et al., 2019	Mandibular 1st molars	Control = TrussAC > TradAC	Yes	Yes	Yes	Yes	Yes	Yes	Yes	CBCT
Augusto et al., 2020	Mandibular molars	TradAC = UltraAC	—	Yes	—	—	Yes	Yes	Yes	Micro-CT
Barbosa et al., 2020	Mandibular molars	TradAC = ConsAC = TrussAC	—	Yes	—	—	Yes	Yes	Yes	Micro-CT
Chlup et al., 2017	Premolars	Control = TradAC = ConsAC	—	—	—	Yes	Yes	Yes	Yes	Not reported
Consentino et al., 2018	Mandibular Molars	Control > TradAC = ConsAC = TrussAC	—	Yes	Yes	Yes	Yes	Yes	Yes	Radiography and external measurement of teeth
Ivanoff et al., 2017	Mandibular Premolars	Control = TradAC = ConsAC	—	—	Yes	Yes	Yes	—	Yes	External measurement of teeth
Karohari et al., 2021	Mandibular 1st molars	Control > TrussAC; Control > ConsAC; Control > TradAC; ConsAC > TradAC; TrussAC > TradAC; ConsAC = TrussAC	—	Yes	—	Yes	Yes	Yes	Yes	External measurement of teeth and Micro-CT
Krishan et al., 2014	Premolars	Control = ConsAC > TradAC	—	—	—	Yes	Yes	—	—	Radiography
	Molars	Control = ConsAC > TradAC								
	Incisors	Control = TradAC = ConsAC								
Lima et al., 2021	Mandibular molars	UltraAC = TradAC	—	Yes	—	—	Yes	Yes	Yes	Micro-CT
Makati et al., 2018	Molars	ConsAC > TradAC	—	—	—	—	Yes	Yes	Yes	Not reported
Maske et al., 2021	Mandibular molars	Control > ConsAC = TradAC	—	—	—	Yes	Yes	Yes	Yes	External measurement of teeth
Moore et al., 2016	Maxillary Molars	Control > TradAC = ConsAC	—	—	—	Yes	Yes	—	Yes	Radiography
Mustafa et al., 2020	Mandibular molars with 2 residual walls	ConsAC > TradAC	—	Yes	Yes	Yes	—	—	—	Not reported
	Mandibular molars with 3 residual walls	ConsAC = TradAC								
Marinescu et al., 2020	Molars	Control = ConsAC > UltraAC > TradAC ^a	—	Yes	—	Yes	Yes	Yes	Yes	External measurement of teeth
Özyürek et al., 2018	Mandibular Molars	Control > TradAC = ConsAC	Yes	—	Yes	Yes	Yes	Yes	Yes	External measurement of teeth
Pereira et al., 2021	Maxillary premolars	Control = ConsAC = TradAC	—	—	—	Yes	Yes	Yes	Yes	Micro-CT

(Continues)

TABLE 5 (Continued)

Reference	Tooth type	Main results	Sample age	Freshly extracted teeth	Occlusal cavity	Control group	Canal shaping	Canal obturation	Tooth restoration	Selection method
Plotino et al., 2017	Premolars Molars	Control = ConsAC = UltraAC > TradAC	—	Yes	—	Yes	Yes	Yes	Yes	External measurement of teeth
Reddy et al., 2020	Mandibular 3rd molar	Control = UltraAC > ConsAC = TradAC	—	—	—	Yes	Yes	Yes ^b	Yes ^c	Not reported
Roperto et al., 2019	Maxillary 1st premolars	Control = TradAC = ConsAC = ConsAC. DW	—	—	—	Yes	Yes	Yes	Yes	External measurement of teeth
Rover et al., 2017	Maxillary Molars	TradAC = ConsAC	—	—	—	—	Yes	Yes	Yes	Micro-CT
Rover et al., 2020	Mandibular incisors	TradAC = ConsAC	—	—	—	—	Yes	Yes	Yes	Micro-CT
Sabeti et al., 2018	Maxillary Molars	Control > TradAC = ConsAC	—	—	—	Yes	—	—	—	External measurement of teeth
Saberi et al., 2020	Mandibular Molars	Control > TrussAC > TradAC	—	Yes	—	Yes	Yes	Yes	Yes	External measurement of teeth
Santosh et al., 2021	Mandibular molars	Control > TrussAC; Control > ConsAC; Control > TradAC; ConsAC > TradAC; TrussAC > TradAC; ConsAC = TrussAC	—	Yes	—	Yes	Yes	Yes	Yes	External measurement of teeth and CBCT
Silva et al., 2020a	Maxillary Premolars	TradAC = UltraAC	—	—	—	—	Yes	Yes	Yes	Micro-CT
Silva et al., 2021a	Mandibular 1st molars	TradAC = UltraAC	—	Yes	—	—	Yes	Yes	Yes	Micro-CT
Spicciarelli et al., 2020	Maxillary central incisors and maxillary 1st premolars	TradAC = ConsAC	—	Yes	—	—	Yes	Yes	Yes	External measurement of teeth
Xia et al., 2020	Premolars	TradAC = ConsAC	—	—	—	—	Yes	Yes	Yes	Micro-CT

Abbreviations: CBCT, cone beam computed tomography; ConsAC, conservative access cavity; UltraAC, ultra-conservative access cavity; TradAC, traditional access cavity; TrussAC, truss access cavity; UltraAC, ultra-conservative access cavity.

^aThe study does not present statistical analysis.

^bThe teeth were filled with calcium hydroxide paste.

^cThe teeth were restored with glass ionomer cement.

Sample selection

One of the most important methodological aspects of research design is the creation of a reliable baseline inasmuch as anatomical discrepancies of sampling may have a direct impact on the outcome. Although it seems logical that a proper anatomical pairing of teeth allocated for each experimental group may compromise the final conclusions, several studies performed sample selection based only on two-dimensional radiographs (Corsentino et al., 2018; Krishan et al., 2014; Moore et al., 2016), external measurement of teeth (Corsentino et al., 2018; Ivanoff et al., 2017; Marinescu et al., 2020; Maske et al., 2021; Özyürek et al., 2017; Plotino et al., 2017; Roperto et al., 2019; Saberi et al., 2020; Sabeti et al., 2018; Spicciarelli et al., 2020) or merely by random allocation into the experimental groups (Chlup et al., 2017; Makati et al., 2018; Mustafa et al., 2020; Reddy et al., 2020). To overcome these sampling limitations, De-Deus et al. (2020) demonstrated that micro-CT technology is the recommended method to pair-match extracted teeth based on their anatomical characteristics (Figure 24). Micro-CT allows several morphometric parameters of the dental hard tissues and the root canal system (volume, surface area, aspect ratio, etc.) to be calculated, thus minimizing the intrinsic anatomical heterogeneity of teeth and improving the internal validity of the study (De-Deus et al., 2020; Silva et al., 2021b). In the context of minimally invasive endodontics, nine studies used the micro-CT approach for sample selection and distribution, assuring the creation of a reliable baseline for comparison. Interestingly, no difference was observed between teeth prepared with TradAC or contracted access cavities in all these studies (Augusto et al., 2020; Barbosa et al., 2020; Lima et al., 2020; Pereira et al., 2021; Rover et al., 2017, 2020; Silva et al., 2020a, 2021b) (Figure 25).

In future studies on access cavity preparation, the anatomical pairing of samples based on morphological aspects of the root canal (volume, surface area and configuration), pulp chamber (volume), and dental hard tissues (total volume, root volume, and crown volume) obtained by micro-CT imaging is essential. Using this methodological framework for sample selection and distribution, the anatomical bias can be minimized.

Sample conditions

Dentine is a hard tissue that is basically composed of water (10%), an organic matrix (30%), and inorganic components (60%) (Kinney et al., 2005). This organic matrix is made up primarily of collagen, and the inorganic

phase consists of apatite crystals (Katz, 1971). The apatite phase contributes to most of the compressive strength that might directly affect hardness, while the collagen phase provides elasticity (Martin & Boardman, 1993). A change in these two phases might contribute to modifications in these physical properties. Over the years, the dentine suffers physiological changes, such as reduction of peritubular fluid, narrowing of the tubular lumen diameter, and calcification (Arola et al., 2017; Kinney et al., 2005), which may negatively impact tooth toughness and ductility, reducing its endurance limit (Arola & Reprogel, 2005; Bajaj et al., 2006; Ivancik et al., 2012; Kinney et al., 2005; Nazari et al., 2009). Previous studies have already reported that the fatigue strength of young dentine (17–30 years) is greater than older dentine (50–80 years) (Arola & Reprogel, 2005). With age, there is usually an increase in the development of parafunctional habits (Lavigne et al., 2008), which may alter the biomechanical responses of the dentine tissue. Nonetheless, this is by far the most overlooked aspect of studies assessing minimally invasive access cavities since only two studies reported the age of the specimens (Table 5).

The storage condition (solution and time) of the specimens used in fracture resistance tests is also another relevant topic as it may have a direct impact on dentine properties (Goodis et al., 1993; Lee et al., 2007), such as the formation of microcracks by dehydration (Shemesh et al., 2018). In the field of dental materials, the technical specification 11 405 states that “*ideally the bond strengths should be measured immediately post-extraction, but this is not generally feasible. It appears that most changes occur in the initial days or weeks after extraction. Therefore, teeth 1 month, but not more than 6 months, after extraction should be used*” (2003). Thus, a close-to-ideal experimental framework for sample selection in resistance to fracture tests should include (i) the creation of well-balanced anatomically experimental groups (reliable baseline), (ii) the selection specimens from patients with similar age, (iii) the use of freshly extracted teeth, and (iv) the storage of the specimens in the same media for the same period of time.

Thermal and mechanical cycling

Thermomechanical cycling simulates natural stresses during oral function on teeth over time that may cause collagen degradation and poor adaptation of restorations (De Munck et al., 2015; Rossomando & Wendt, 1995; Santos & Bezerra, 2005), affecting mostly the fracture resistance of endodontically treated teeth (Sarabi et al., 2015; Scotti et al., 2011) (Figure 26). Therefore, thermal and/or mechanical cycling simulating oral masticatory function and

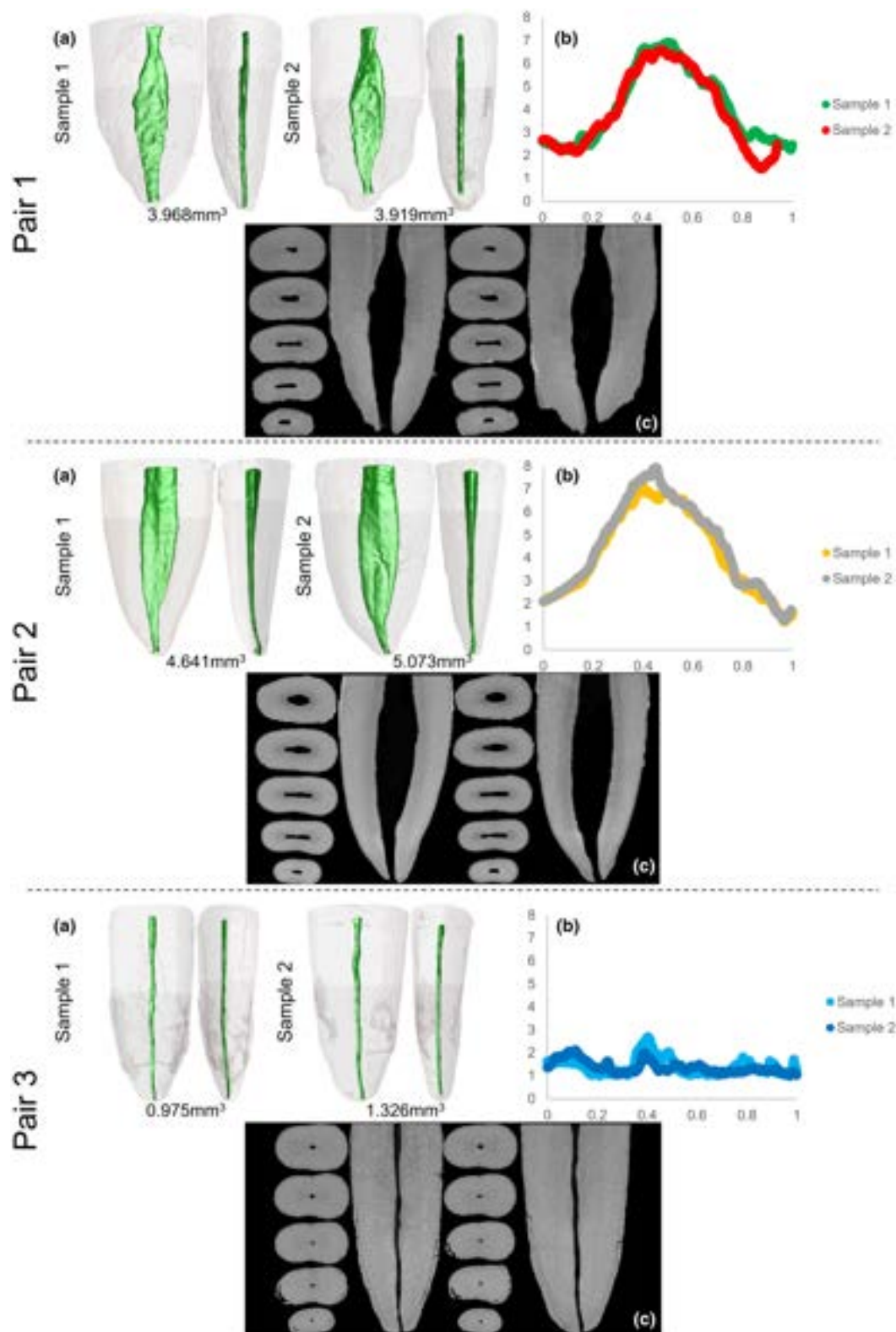


FIGURE 24 Pair-matching process for sample distribution into groups is based on volume, (a) 3D configuration, and (b) aspect ratio of the root canals, which are plotted on graphic curves and calculated using (c) all cross-sectional images obtained by micro-CT. This image shows three pairs of single-rooted teeth matched according to abovementioned parameters

the natural ageing process in the mouth have been recommended with the aim of optimizing the fracture resistance assays.

In the context of minimal access preparation, three studies simulated ageing by thermo and/or mechanical cycling the specimens before the fracture resistance

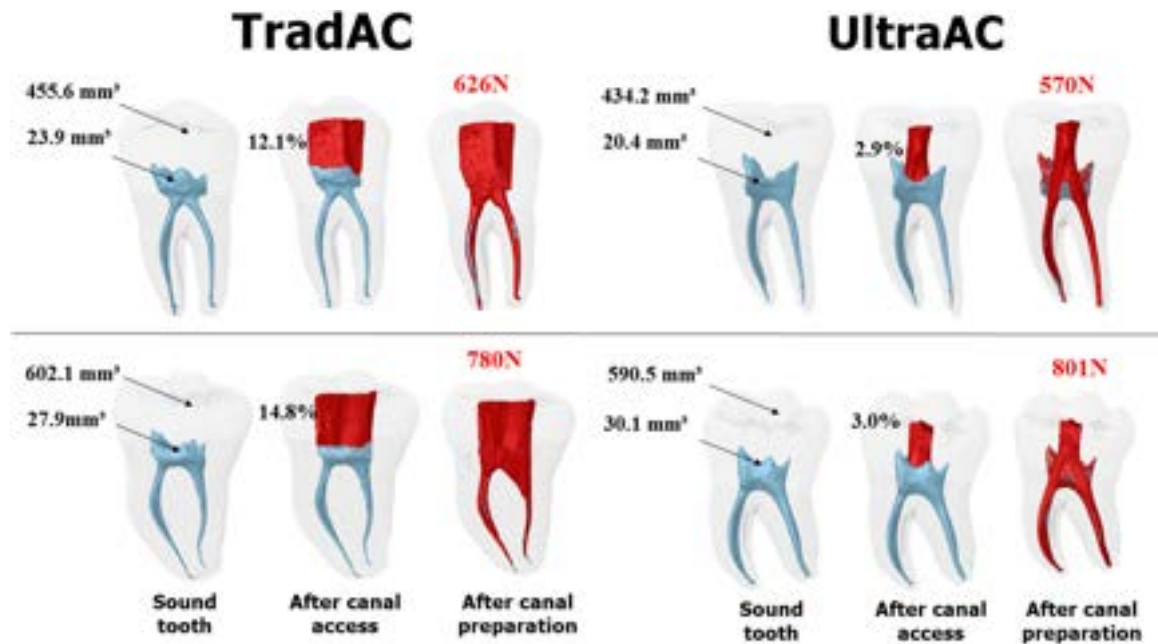


FIGURE 25 Pair-matched technique based on anatomical aspects of selected teeth by means of micro-CT imaging. This figure shows representative 3D images of four mandibular molars prepared with TradAC and UltraAC, demonstrating the dental tissues at the baseline (sound tooth, root canal system in blue), and after access cavity and canal preparations (areas in red). It is important to highlight the volumes (in mm³) of the crown and pulp chamber before canal access, the percentage volume reduction of dental tissues from the crown after access cavity preparation, as well as the fracture resistance based on the maximum load to fracture values (in Newtons)



FIGURE 26 A thermomechanical cycling device (ER-37000; ERIOS), in which it is possible to simulate oral masticatory function due to the cyclic load applied to the sample, and also to simulate ageing in the oral cavity with variable temperature promoted by the device

test (Lima et al., 2021; Saberi et al., 2020; Santosh et al., 2021). Saberi et al. (2020) reported that without thermocycling, the fracture strength of teeth with TradAC and TrussAC was similar to that of the control but, when exposed to thermocycling, TradAC teeth had the lowest fracture strength. Similarly, Santosh et al. (2021) demonstrated that teeth with TrussAC and ConsAC subjected to

thermomechanical cycling had greater fracture resistance than with TradAC. On the contrary, Lima et al. (2021) found no difference in the maximum load to fracture amongst TradAC and UltraAC after root canal treatment and thermomechanical cycling. The conflicting results might be explained by differences in the experimental setups. While Saberi et al. (2020) and Santosh et al. (2021)

selected their samples based on the external measurement of the crown (Sabeti et al., 2020) or CBCT images (Santosh et al., 2021), Lima et al. (2021) performed anatomical matching using micro-CT technology. This latter approach increased the internal validity of the study as well as the reliability of the results.

Although thermomechanical ageing can be considered a methodological improvement, this approach does not reproduce well the clinical scenario since multiple factors—age, sex, weight, body mass index, medical condition, presence of premature contacts and parafunctional habits, type of dental arch, vertical skeletal patterns, different types of functional occlusion, type of static occlusion, tooth type, antagonistic teeth, overjet, overbite—cannot be replicated. Moreover, the real magnitude of the bite forces of mastication can be low enough to not cause fracture. Then, the creation of age-controlled and anatomically well-balanced experimental groups seems to have higher methodological relevance than thermomechanical cycling for biomechanical assessments.

Static and dynamic loading fracture

In endodontic research, there is a common belief that an effective experimental model should reproduce the clinical scenario. A good example was the rationale described in a recent editorial which stated that traditional static loading tests should no longer be acceptable since “clinically, most failures are caused by cyclic fatigue with a subcritical load which is much lower than the load capacity” (Ordinola-Zapata & Fok, 2021). However, it does not present any experimental validation to support the proposed methodology and recommends that future studies on this subject, which also includes minimal access cavities, should use only the cyclic fatigue approach, also known as dynamic loading test, to evaluate the fracture resistance of teeth (Figure 27). Although it seems logical, it is important to remember that loading tests do not intend to reproduce the clinical settings. Rather, they are designed to effectively compare the limited resistance capacity of a given material, technique, or situation under well-controlled *ex vivo* conditions, providing reliable and reproducible data to rank materials/techniques with low ethical costs and in a preliminary, rapid, and affordable way. Thus, the main role of a close-to-ideal pre-clinical laboratory study is to somehow be able to predict the clinical performance of materials/techniques and, for that goal, it is not mandatory to reproduce the clinical setting. This objective was partially achieved in the adhesive-dentistry field, in which a positive correlation between the bond strength of the adhesives to dentine (laboratory data) and their

effectiveness in the clinical environment was found (Van Meerbeek et al., 2010). Certainly, the proposal of new methodologies, such as thermal and mechanical cycling, is necessary, but the combination of static loading assays to other biomechanical tests can still provide important insights for a better understanding of a material and/or technique.

Finite element analysis

Finite Element Analysis (FEA) is a widely used numerical analysis that has been applied successfully in many engineering and bioengineering areas since the 1950s. This computational numerical analysis can be considered the most comprehensive method available to calculate the complex conditions of stress distributions and predicting the sites of stress concentrations, which are the most likely points of failure initiation within a structure or material (Soares et al., 2012). In dental research, FEA has been used effectively in many studies and, more recently, it was applied to assess the stress concentration areas in teeth with different types of simulated access cavities (Elkholy et al., 2021; Franco et al., 2020; Jiang et al., 2018; Roperto et al., 2019; Sabeti et al., 2020; Wang et al., 2020; Yuan et al., 2016; Zhang et al., 2019b). Overall, the high stress concentration areas at the cervical region of the tooth increases the volume of the access cavity preparation and becomes larger, suggesting that the cavity size could compromise the fracture resistance of root filled teeth (Figure 28).

Although the advantages of FEA compared to testing methods include low operating costs, reduced time to carry out the investigation, and the possibility to provide information that cannot be obtained by experimental research, FEA cannot replace traditional laboratory studies, requiring their validation to prove their results (Soares et al., 2012). Roperto et al. (2019) associated the FEA with a fracture-strength method to assess the effects of access cavity configuration (ConsAC, ConsAC.DW, and TradAC) on stress distribution, fracture resistance, and fracture mode. FEA revealed similar stress distribution among the experimental and control (no access cavity) groups, while fracture resistance and failure mode using extracted teeth demonstrated similar results. Pereira et al. (2021) evaluated the impact of ConsAC and TradAC on root canal preparation and restoration using micro-CT, biomechanical behaviour through FEA, and fracture resistance with extracted teeth. Similar to the results of Roperto et al. (2019), the endodontic access cavity did not influence the biomechanical behaviour of root filled and restored teeth (Figure 29). Elkholy et al. (2021) combined FEA with occlusal fingerprint analysis. The occlusal fingerprint analysis was performed by mapping the occlusal

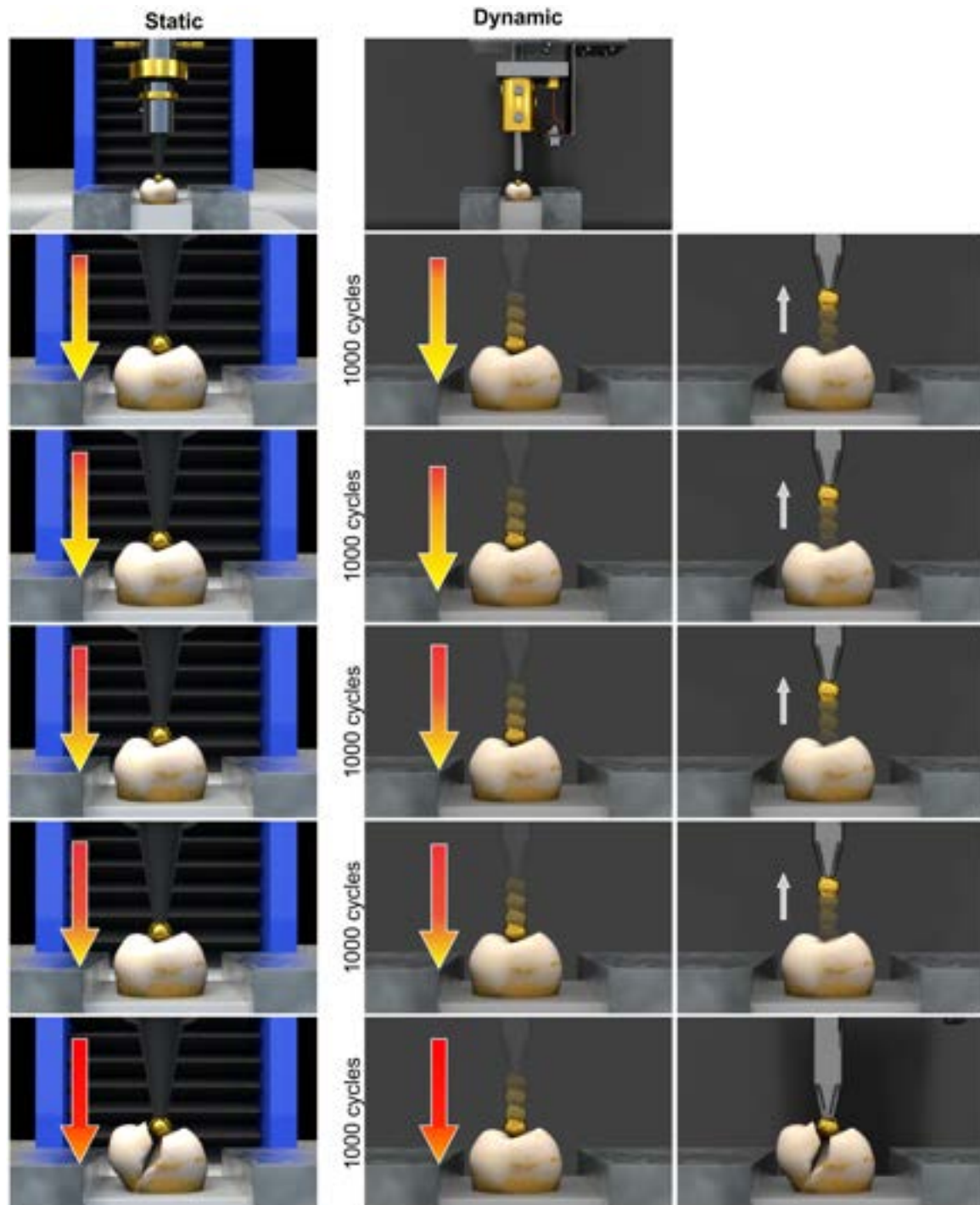


FIGURE 27 Schematic representation of static (left) and dynamic (right) loading tests. In the static loading test, a continuous compressive force is applied until failure and the maximum load to fracture is registered (usually in Newtons). In contrast, in the dynamic loading test, load amplitude and frequency representative of clinical conditions are applied. One possible problem is that these representative clinical load conditions make the test unfeasible due to the prohibitively long time to fracture a tooth in a laboratory setting. For this reason, a step-stress cyclic loading methodology has been suggested. Within this method, cyclic fatigue is carried out at specified loads with increasing amplitudes, each for a specified number of cycles (or time) until the test specimen fails

contacts obtained by digitally scanning the antagonist tooth to determine the loading areas on the subject model in an effort to simulate the clinical biomechanic condition. The authors concluded that the tooth's life span was

significantly affected by the access cavity design rather than canal enlargement.

Notwithstanding that FEA analysis has demonstrated differences in stress distribution when comparing teeth

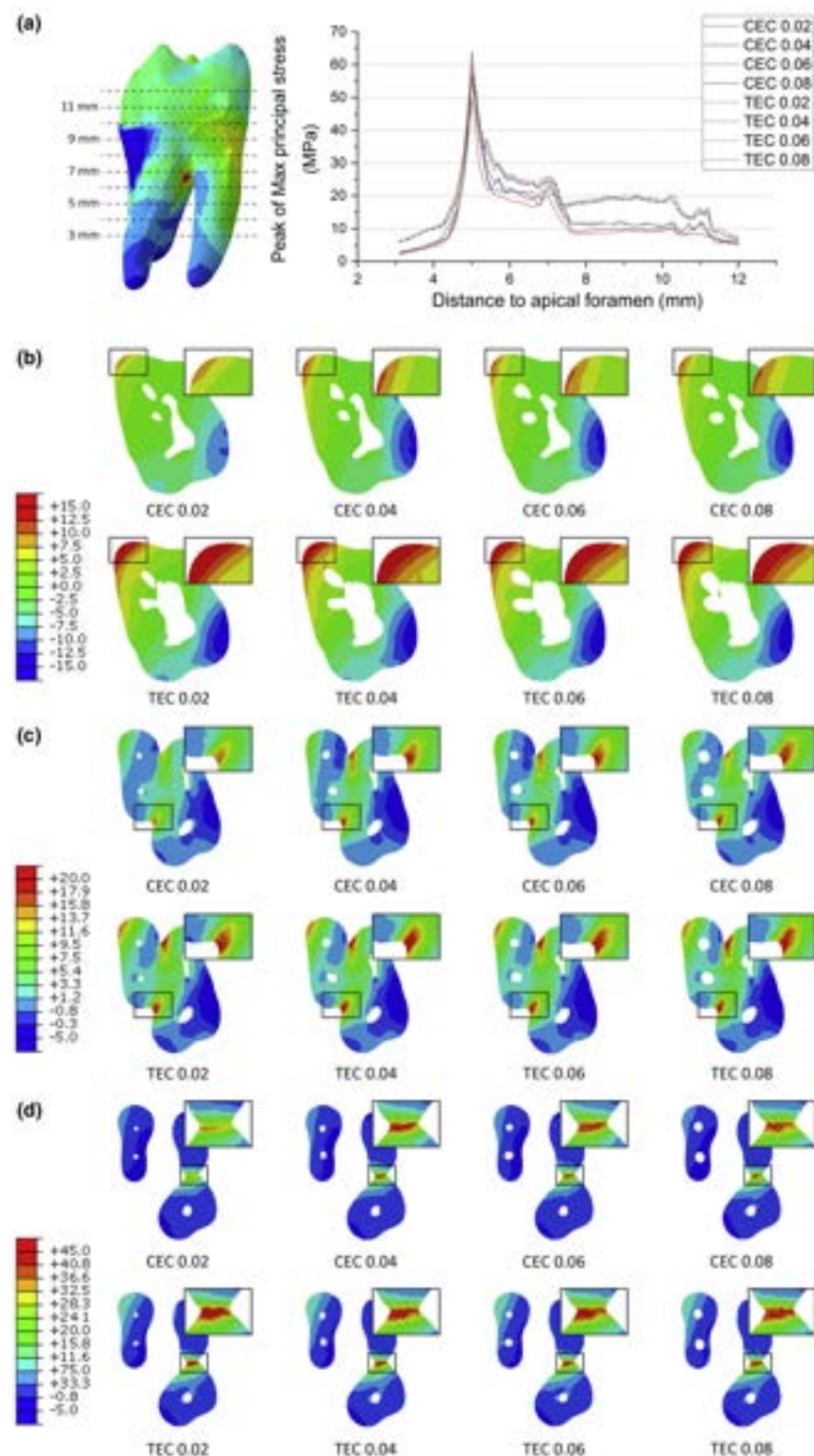


FIGURE 28 Influence of access cavities and tapers of root canal preparation on the fracture resistance of root-filled maxillary first molars by the finite element method and Weibull analysis. (a) Peak of maximum principal stress vs. distance to the apical foramen and distribution of maximum principal stress on the section of (b) pulp chamber floor (9 mm to apical foramen) and (c and d) root furcation areas (7 mm and 5 mm to apical foramen). Maximum principal stress was concentrated on the buccal side of the mesiobuccal root at the level of the pulp chamber floor and root furcation. Smaller stress concentrations were detected in ConsAC than TradAC. Tapers of canal preparations had less effect on stress distribution (Reprinted from Wang et al., 2020 with permission)

with different types of access cavities, in some studies that combined FEA and other experimental methods, this difference was not significant. FEA is the compilation of physical laws and material properties expressed in a theoretical model that describes interactions between various factors and properly capable of improving the understanding of

clinical insights, but it is limited for the inability of a precise description of biomechanical dynamics of teeth and periodontal structures (Soares et al., 2012). Therefore, the lack of understanding of the reality increases the limitations of FEA when compared to experimental models and, therefore, although FEA may improve knowledge in

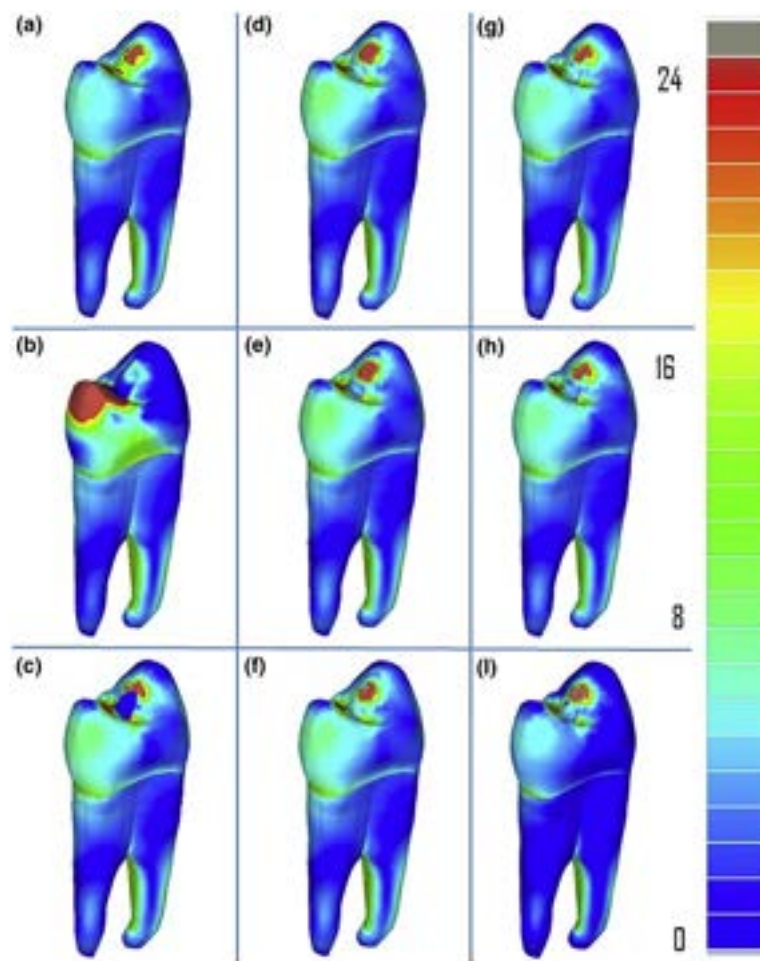


FIGURE 29 Impact of ConsAC on root canal preparation, coronal restoration, and biomechanical behaviour of teeth prepared with different shaping systems and restored with different materials. TradAC was used as a reference for comparison. Micro-CT, finite element analysis, and fracture resistance methodologies were combined. The von Mises stress distributions (MPa) in dental structure obtained in the (a) sound tooth, (b) TradAC with temporary restoration, (c) ConsAC with temporary restoration, (d) TradAC restored with conventional composite resins, (e) TradAC restored with bulk fill composite resins, (f) TradAC restored with bulk fill flow composite resin combined with conventional composite resins, (g) ConsAC restored with conventional composite resins, (h) ConsAC restored with bulk fill composite resins and (i) ConsAC restored with bulk fill flow composite resin combined with conventional composite resins. The results demonstrated that the endodontic cavity did not influence the biomechanical behaviour of restored teeth (Reprinted from Pereira et al. [2021] with permission)

a given situation, the conclusions of studies using solely this method must be interpreted carefully.

EDUCATIONAL CONSIDERATIONS

Endodontics is largely recognized as a technically demanding dental specialty, requiring the use of very specific and complex armamentarium and diligent attention to details in order to reach the basic technical goals of the treatment (Davey et al., 2015). The required familiarization with the technique turns out to be the greatest educational challenge since it embraces the need to develop very specific visual and tactile perceptions that can only be achieved after long-term practice driven by extensive self-learning. Thus, the process of learning a technique, that is recognized as

meticulous and requires prudence along the step-by-step development of very specific technical abilities, is usually aligned with a long and tough educational curve that requires a lot of attention and dedication by the apprentice (Kahneman, 2013). In simple terms, complex techniques are associated with longer learning curves.

The main purpose of the access cavity is to provide access for the endodontic instruments to work in the root canal system, and its effectiveness is highly dependent on the visualization of the canal orifices. Without proper visualization, canals may be missed, increasing the odds of endodontic failure (Costa et al., 2019). Although one may argue that contracted cavities can interfere with the visualization of canal orifices, in fact, a skilled operator is able to identify them under a limited operative field provided adequate armamentarium, such as microscope, ultrasonic

tips, and proper dental mirrors are used. While this is feasible in practice, it is, on the other hand, counterintuitive from an educational point of view. The complexity involved in the learning process of identifying root canal orifices through minimal cavities requires a significant time commitment, focus, and energy from the trainee to overcome this difficult technical step. Thus, the complete removal of the pulp chamber roof recommended for traditional access cavities cannot be undermined since it is the easiest and most reliable way to achieve access to the root canals, allowing the possibility of a full inspection of the pulp chamber floor from where essential information can be obtained to drive the operator towards effective location of the canal orifices. Therefore, when considering the high technical demanding and steep learning curve introduced by minimal access cavities, it is important to frame the related issues that can increase the complexity involved in the learning process as follows:

- a. *Canal orifice location.* In order to locate the root canals, students usually learn to add a preconceived anatomical reference of where the entrances should be with a complementary radiographic exam to enable a 3D mental plan of the pulp chamber format and orifice locations. Although this procedure seems to be simple, calcified canal entrances and narrow root canals make this task counterintuitive, which helps explain the high prevalence of missed canals, even when traditional access cavities are performed (Baruwa et al., 2020; Costa et al., 2019). Consequently, the full inspection of the pulp chamber floor is highly recommended, especially in multi-rooted teeth. On the other hand, this approach cannot be performed entirely using minimal cavities because the roof is removed only up to a limit in which visualization of the area anatomically designated to canal orifices is confirmed. That situation can lead to when extra anatomical details being missed. Preoperative CBCT assessment can overcome this limitation, but this resource is certainly not readily available in most dental schools worldwide.
- b. *Instrument control.* In order to properly shape, disinfect, and fill the root canal system, instruments need to gain access to allow their safe intracanal manipulation. Regardless of the instrument type, root canal assessment is dependent upon an ideal angle of entrance—given to the tip of the instrument—combined with the visualization of the target point at the pulp chamber floor—granted by an indirect mirror visualization simultaneously with tactile inspection. Using a mirror-guided angle of penetration facilitates learning; however, an adequate field of view is required to allow the mirror to be positioned sideways to the instrument or hand piece in such a way that the hand can keep following the angle, while the mirror allows visualization.

Under minimal access cavities, the attempt to use a mirror-guided canal penetration is usually impossible as both mirror and instrument/handpiece compete for the same angle to permit simultaneous visualization. Therefore, most of the time, canal preparation is only achieved with tactile perception, a skill difficult to acquire by trainees. To reduce the risk of accidents in the initial steps of root canal preparation, the use of instruments with controlled memory have been advocated so that they can be pre-bent to facilitate the angle of penetration. Again, these technological resources are not readily available in all dental schools, and they also require a long learning curve to be mastered.

- c. *Pulp chamber cleaning.* One of the most troublesome and time-consuming procedural steps that appear as a consequence of minimal access cavities, especially the TrussAC, is the cleaning of the pulp chamber during chemomechanical preparation and after canal filling procedures. After canal orifice location, it is mandatory to clean the remaining roof corners from debris, bacteria, and/or pulp tissue. To accomplish this task, it is necessary to use modified instruments, such as angled ultrasonic tips, that are not readily available and may not be simple to operate by trainees. Similarly, after the canal filling phase, the task of removing filling remnants from the roof corners is challenging and requires patience and diligence to achieve their complete removal. Reports from practitioners indicate that this phase consumes a high percentage of the chair time and is perceived as an annoying requirement imposed by minimal access cavities.

From an educational standpoint, it seems unwise to make endodontic practice even more technically demanding and complex to learn than it already is considering that even trained and skilled professionals undeniably face a substantial increase in chair time while attempting to perform treatment through minimal access cavities. The inflation of the learning curve is, thus, proportional to the technical complexities involved in mastering the armamentarium needed to perform the technique. Therefore, minimally invasive access preparations are the opposite of the trend towards technical simplification that has been accomplished lately in endodontics by the mechanization of root canal preparation. In a world where a shortage of formal educational time is constantly being proposed and equipment is not easily available for every dental student, it is difficult to believe that such educational challenges can be easily overcome. This is why the proliferation of such techniques in social networks produces an educational disservice by encouraging clinicians to ignore basic rules of disinfection and prepare minimal access cavities through flawed composite restorations, decayed tissue, or insufficient crowns, as it can be seen in countless cases

posted on social media. Aristotelian reasoning states that the natural condition of human beings is to think and, as such, there is an irrefutable need to discuss the educational impact of minimal access cavities by those involved in teaching endodontics. Undeniably, performing endodontic treatment through small cavities is highly dependent on labour- and time-intensive training and increased chair time, ultimately requiring a longer and more complex learning curve. From an educational standpoint, this seems unwise considering the risk of potentially raising the incidence of procedural accidents and complications without any significant advantage in terms of tooth strengthening, as current laboratory reports suggest.

COST-BENEFIT ANALYSIS OF MINIMAL ACCESS CAVITY: A CRITICAL VIEW

Treatments in healthcare usually consider the optimum equilibrium between its biological cost and the expected benefit (cure). In other words, the disease is treated at the expense of side effects that can be considerable or negligible depending on the best cost/benefit balance. There is an overall belief that more aggressive treatments would entail higher benefit for the patient, a rationale called 'the more, the better', which is nothing more than a mechanistic paradigm supported on biological plausibility towards the benefit (Correia, 2011). Nevertheless, certainly there is a moment in which the increase in treatment aggressiveness may lead to more undesired side effects (high biological cost), with no necessary increase in the benefit.

In endodontics, the need to make clinical decisions under the concept of the cost/benefit dichotomy is also a major rule. This might be critical when considering the ideal balance between the amount of dental tissue that should be removed (biological cost) to reach an appropriate disinfection level (benefit). Because there are laboratory (Bürklein et al., 2012; Paqué et al., 2005) and clinical (Saini et al., 2012) studies that corroborate the 'the more, the better' paradigm using concepts such as straight-line access, apical canal enlargement, large-tapered instruments, and profuse irrigation with high concentrated solutions, among others, the supposedly higher biological cost imposed to the dental tissues by these techniques can be implicated as the major cause of tooth loss and, thus, root fracture (Clark & Khademi, 2010a; Garcia-Guerrero et al., 2018; Haueisen et al., 2013; Yoshino et al., 2015). Moreover, when looking from an epidemiological perspective, in which root fracture is more prevalent in endodontically treated teeth (Clark & Khademi, 2010a; Garcia-Guerrero et al., 2018; Haueisen et al., 2013; Yoshino et al., 2015), the minimal access preparation concept (Bürklein &

Schäfer, 2015; Clark & Khademi, 2010a; Gluskin et al., 2014; Ruddle, 2014) brings to the fore the rationale that by reducing the amount of dentine removed, the teeth becomes less brittle, consequently reducing the fracture rate. Although plausible, a relevant question may arise: how much would it be possible to reduce the biological cost (tooth tissue removal) without losing the benefits (disinfection and apical healing)? While this is not obvious from a clinical perspective, a sceptical way of thinking would believe that just as, at a certain point, being more aggressive does not increase the benefit of the therapy proportionally, the contrary would be also valid, that is, being less aggressive may not consistently reduce the biological cost (fracture rate) (Table 6).

The main argument of supporters of minimal access preparation is grounded on saving the dentine, while little emphasis is given to disinfection control. This is due to the fact that recent technological advancements in instrument properties allow clinicians to reliably reach and fill the root canals up to the canal terminus even under extremely small access cavities, giving a false impression of an adequate disinfection. In other words, the discussion on disinfection control is overlooked because many dentists believe that a much higher risk of post-treatment disease is likely when the root canal filling is short of the canal terminus, than if the canal preparation is parallel, non-tapered, and narrow. In this sense, the interplay between the argument of reducing the fracture risk of root-filled teeth, the current relative simplicity to obtain certain technical parameters, and the lack of focus on infection control result in the rationale that day-after-day the minimal access cavity concept is rational and logical. Instead, the treatment choice for infected root canals should be based on the best cost-benefit balance for infection control. Therefore, using the asymmetrical principle (Correia, 2011), a concept in which the clinical evidence is balanced with plausibility evidence (given by laboratory studies) under a cost/benefit rationale, three treatment options are outlined in Table 5, where minimal access preparation approaches are associated with the weakest level of evidence with negative results for both cost and benefit (Augusto et al., 2020; Barbosa et al., 2020; Corsentino et al., 2018; Moore et al., 2016; Özyürek et al., 2018; Sabeti et al., 2018; Vieira et al., 2020), which means that minimal access preparation is NOT supported by solid evidence.

From a scientific perspective, it is wrong to place cost before benefit, although this is not uncommon in the health field. It is not appropriate to propose a technique based only on its safety or biological cost-reduction as it makes little sense. If the dose of a drug is reduced, focused only on minimizing its side effects, the therapy may become useless if it compromises the benefit. That is the

TABLE 6 Cost/benefit for an evidence-based decision towards access preparation and root canal enlargement

	Treatment A Conservative	Treatment B Standard	Treatment C Aggressive
Preparation technique	Conservative or ultraconservative access cavity and an apical final size below 25, taper 0.02	Straight-line access cavity and apical final size 25 taper 0.04 or 0.06	Straight-line access cavity and apical final size 30 (or more) and taper 0.06 or 0.08
Cost (dentine removal, fracture resistance)	Similar dentine removal to standard (<i>in vitro</i>) No superior fracture resistance in some tooth (<i>in vitro</i>) (Augusto et al., 2020; Barbosa et al., 2020; Chlup et al., 2017; Corsentino et al., 2018; Ivanoff et al., 2017; Lima et al., 2021; Maske et al., 2021; Moore et al., 2016; Özyürek et al., 2018; Pereira et al., 2021; Roperto et al., 2019; Rover et al., 2017; Sabeti et al., 2018; Silva et al., 2020, 2021; Spicciarelli et al., 2020; Xia et al., 2020) No clinical data	Lower fracture resistance than no treatment (<i>in vitro</i>) (Corsentino et al., 2018; Karobari, 2021 #34563; Maske et al., 2021; Moore et al., 2016; Özyürek et al., 2018; Saberi et al., 2020; Sabeti et al., 2018; Santosh et al., 2021) Observational data suggesting association of endodontic treatment and fracture rate (Fuss et al. 1999)	More dentine removed and lower fracture resistance (<i>in vitro</i>) (Sabeti et al., 2018) No clinical data for fracture rate
Benefit (disinfection, healing rate)	Compromised disinfection (<i>in vitro</i>) (Moore et al., 2016; Vieira et al., 2020) No clinical data	Superior disinfection than conservative (<i>in vitro</i>) (Moore et al., 2016; Vieira et al., 2020) Longitudinal data on success rate over 75% (Farzaneh et al. 2004)	Superior disinfection than standard (<i>in vitro</i>) (Bürklein et al., 2012; Paqué et al., 2005) Similar healing rate than standard. (Saini et al., 2012)
Overall quality of evidence	Weak (negative <i>in vitro</i> effect for cost and benefit)	Strong (negative observational for cost and positive clinical for benefit)	Moderate (negative <i>in vitro</i> for cost and similar clinical for benefit)

case for minimal access preparations, especially when no evidence of a significant increase in fracture resistance by most of laboratory assays has been reported (Silva et al., 2020c).

In spite of the lack of strong evidence to support minimal access preparations—even after more than a decade following its inception (Clark & Khademi, 2010a)—the concept is seen as a modern trend that follows the natural footsteps of care in medicine. In fact, medicine has moved rapidly towards minimally invasive treatments based on advance in the field of microsystem engineering, required to miniaturize high-tech devices, as well as, nanotechnology and high-resolution imaging tools for diagnostics and guidance of surgical instruments. These have resulted in an unprecedented improvement in the capacity to access difficult-to-reach areas while reducing injury to adjacent tissues and the surgical risks involved while, at the same time, improving the healing rate (Pache et al.,

2017). Several surgical protocols have moved from standard open access into minimally invasive techniques and have become the gold standard in many areas (AlAsseri & Swennen, 2018; Cloyd, 2019; Costantino & Mullen, 2019; Garmpis et al., 2019). Interestingly, for instance, the minimal invasion provided by laparoscopic-guided surgeries does not compromise the visual accuracy and accessibility to the operated area. Instead, micro-systems, miniaturized cameras, and microtools provide full and adequate vision and access to the operating field (Figure 30). Thus, the biological cost is reduced without impacting negatively on the benefits or compromising the ability of the clinician to execute the procedure adequately. On the contrary, an immediate consequence of minimal access cavities is a significant reduction in root canal visualization and location. It is not surprising that the literature reveals various negative effects related to canal orifice location, iatrogenic deviations, instrument fractures, and tooth discoloration as



FIGURE 30 External (top) and internal (bottom) views of an abdominal laparoscopic surgery. Although the abdominal incision is conservative, following the minimally invasive concept, the internal visualization of the operation field is fully granted and not compromised by the constricted access (Courtesy of Dr. Roclides Castro de Lima), which contrasts with the minimally invasive access cavities in endodontics as the visualization of the pulp chamber and the root canals' location is invariably compromised

consequences of minimal access preparations (Silva et al., 2020c). Compromising internal visualization of the internal anatomy of teeth consistently places minimal access cavities on the opposite side compared to minimally invasive treatments in the medical field, and, as such, should not be compared.

FINAL REMARKS: SHIFTING THE BURDEN OF PROOF

Minimal access cavity preparation has been promoted as a patient-centred clinical approach, while the traditional access cavity is being framed as a dentist-convenience-centred technique. At a first glance, the argument is appealing since dentine conservation through minimal cavities is supposed to be achieved according to the clinical conditions of teeth, while the traditional approach is based on standardized shapes to grant straight access to all canal orifices. Thus, the minimally invasive concept usually advocates the importance of leaving as much as possible of the pulp chamber roof supported by the hypothesis

that this is relevant to maintain the overall resistance strength of teeth and, consequently, their long-term survival, which is the key argument for the so-called patient-centred approach. Although the idea of soffit preservation could be easily refuted by the experimental or clinical evidence to validate it, the current methods to study tooth preservation over time are limited and, therefore, still open to debate. In fact, the interplay between the lack of adequate laboratory methods and long-term clinical trials is responsible for the uncertainty around this topic ending up in being more intuition-guided than actually knowledge-guided.

To demonstrate how uncertainty somehow sets the tone in the decision-making for minimal access cavities, the concept coined by Tannert et al. (2007) can be used, which categorizes uncertainty as subjective or objective. Both uncertainties derive from the lack of confidence on a specific subject matter. Subjective uncertainty is the lack of confidence in a general rule or the uncertainty is grounded on moral principles, while objective uncertainty is the lack of confidence in a scientifically demonstrated mechanism. Subjective uncertainty drives the process towards an intuition- or ruled-based decision, while the objective uncertainty should produce a more knowledge- or rationale-based decision making, since the scientific method must be used to justify the uncertainty. Supporters of minimal access cavities are not focused on validating their technique by scientific methods (objective uncertainty); instead, they ground their uncertainty towards conventional access preparation by denying the general rule of removing the entire roof of the pulp chamber (subjective argument), posing as a moral and ethical way to practice a patient-centred care, focused on a supposed (scientifically unproven) long-term benefit of the soffit preservation. It is also important to highlight that the traditional concept of access cavity preparation does not place the patient as a secondary consideration. Rather, the complete removal of the pulp chamber roof respects important aspects of infection control, increasing the odds of canal orifice location and reducing the risk of procedural errors.

Even though no clinical prospective study has been published, several cases treated under the minimally invasive access cavity concept are appearing on social media and dental meetings demonstrating healed lesions in infected cases. The fact that healing is possible in individual cases does not mitigate the necessity of assessing in a systematic and prospective way how predictable this treatment mode is not only by providing similar or superior apical healing rates but also proving its value on reducing the fracture rate of filled teeth compared to standard counterpart treatments. It is essential that the minimally invasive access concept passes through populational validation;

otherwise, its clinical application cannot be considered worthwhile. In the current context, where the benefit of minimal access cavities is not clear-cut, it should not be advocated as being superior to the traditional approach (Silva et al., 2021c). In the health science field, the burden of the proof rests on proving the efficacy (benefit) of a treatment or intervention. The nonexistence of such an effect is the basic concept given by the null hypothesis in a scientific study. Yet, even more than 10 years after the first opinionated article on the topic (Clark & Khademi, 2010a), there is no experimental or clinical evidence on neither the safety of this procedure nor its positive impact on treatment outcome. Therefore, despite the passionate way that individuals defend one side versus the other, the current body of evidence is weak, immature, and incomplete to establish a proper decision-making process (Silva et al., 2021c).

CONFLICT OF INTEREST

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

ETHICAL APPROVAL

There are no ethical considerations as this is a review article discussing previously published articles. This review does not report any new experimentation involving humans or animals.

AUTHOR CONTRIBUTIONS

Emmanuel João Nogueira Leal Silva : Conceptualization, writing, review and editing (lead); Gustavo De-Deus: Conceptualization and writing (lead); Erick Miranda Souza: Writing and editing (equal); Felipe Gonçalves Belladonna: Writing and editing (equal); Daniele Moreira Cavalcante: Writing and editing (equal); Marco Simões-Carvalho: Writing and editing (equal); Marco Aurélio Versiani: Conceptualization, writing, review and editing (lead).

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